The Surface Hydrologic Cycle of the United States Western Basins Estimated from Operational Eta Model Forecasts

Yan Luo

Department of Meteorology,
University of Maryland at College Park,
College Park, Maryland

Submitted in partial fulfillment of the requirement for the degree of

Master of Science in Meteorology

April 2004

Advisor: Dr. Ernesto Hugo Berbery

Abstract

The surface hydrologic cycle of western basins in the United States using NCEP's Eta model forecasts is investigated and compared with available observations and estimates resulting from the macroscale hydrologic Variable Infiltration Capacity model (VIC). As the operational version of the Eta model, during recent years it has experienced changes and upgrades and this fact may have affected the model output. We discuss these potential effects on the surface hydrological cycle by evaluating the precipitation forecast performance using an 8-yr period (June 1995-May 2003) 12-36 h forecast dataset and analyze the land surface hydrological processes based on the more recent 5-yr period (June 1998-May 2003) model forecast products.

The focus of this study is on the Columbia River Basin (CRB) and Colorado River Basin (CORB) in the western United States, which have many important features typically found in the hydrological cycle, and a number of noticeable differences and similarities in the aspects of the surface hydrologic cycle have been detected. The precipitation evaluation brought our particular attention to the underestimation of observed precipitation without topography correction and model parameterization schemes themselves, and their link to overestimated model precipitation over the Columbia basin during cold season and underestimated model precipitation over the Colorado basin during summertime. Owing to the complex topography and climate regime in the western basins, there is a fairly large disparity between observed precipitation with or without topography correction. A difference of about 30% is found over the Columbia basin and about 14% over the Colorado basin. As excessive model forecast precipitation is mainly observed during winter months in the Columbia basin, large biases were identified, and related mostly to underestimate of gauge-based precipitation measurements, and in particular, the large scale precipitation component of the model itself. On the other hand, this study also suggests that the largest summer negative bias over the Colorado basin is tend to be induced by the underestimated convective precipitation component.

The region distribution of the estimated other surface hydrological variables is characterized by wet, deep runoff, deep snow accumulation in most Columbia River Basin, with dry, thin runoff and snow accumulation in certain regions of the Colorado River Basin. The hydrological variables in the Eta model capture the basic features of results derived from VIC model, producing qualitatively in general agreement and physically reasonable surface hydrologic cycle at regional-to-large scales. As expected, the largest differences are found near mountains and the western coastline. Important differences arise in their mean annual cycle over the two basins: 1) Compared with VIC model, the Eta model has a stronger annual cycle amplitude and larger interannual variability; 2) snow melt in the Eta model precedes that of VIC by two months, and this phase shift is also reflected in the other variables. Differences are largest during spring, and as the seasonal progress toward late fall and into winter the estimates become closer.

Promising improvements have been found in the model performance in terms of quality of the forecast precipitation and in the reduction of the residual term of the surface water balance. Both effects are most evident in the last three to four years, suggesting that at least similar (or better) quality will be found in studies based on the recently released North American Regional Reanalysis dataset.

1. Introduction

The Columbia River that flows from the North American continent into the North Pacific Ocean is the third largest river system in the United States. Its basin covers portions of seven western states and Canadian province of British Columbia, and drains about 85 percent of the northwestern part of the country with a drainage area of 668,000 km^2 (Fig.1). The basin's climate, strongly affected by orographic influences, is partly continental and partly marine. The region receives most of its precipitation in the winter months, with less than 20% during June-August (Pulwarty and Redmond 1997). The hydrology of the CRB is dominated by snow accumulation and melt (Leung and Ghan 1999), as the runoff peaks strongly in spring when snow melts and its shifts are associated with winter snow accumulation. Thus, the Columbia River is primarily a snowmelt-driven system; it has relatively high runoff per unit area and low reservoir storage relative to the mean annual inflow (Pulwarty and Redmond 1997).

The Colorado River heads in the Rocky Mountains and flow generally west and south, and then discharge into the Gulf of California. The Colorado basin covers about 637,000 km^2 and spreads over parts of seven states and Mexico (Fig.1). High elevation snow pack in the Rocky Mountains contributes about 70 % of the annual runoff, and thereby the seasonal runoff pattern throughout most of the basin is heavily dominated by winter snow accumulation and spring melt (Christensen et al. 2004). The basin is one of North American Monsoon affected regions and much of the basin is arid. The summer monsoon precipitation, although largest over northwestern Mexico, extends over the southwestern states and serves as a secondary source of water for the basin. The Colorado River system is also one of the most heavily regulated for providing water supply, irrigation, flood control and hydropower to a large area of the U.S. Southwest, which is known as the "Lifeline of the Southwest".

These two basins have been chosen as GAPP (GEWEX Americas Prediction Project) study areas. The reason is that their hydrologic cycle plays such a critical role in the water resources of the western United States, thus, a better understanding and description of all aspects of the mean hydrological cycle of the western basins is thus vital. However, many hydrologic processes relevant to these basins are either not measurable or are poorly measured. As will be addressed later, in some situations, topography and geography distribution have critical impacts on water cycle of a basin and these potential impacts have been demonstrated in a number of studies. For example, precipitation is measured at irregular and widely spaced stations in gauges that may highly underestimate the true precipitation, owing largely to the effect of wind on snowfall (Groisman and Legates, 1994). Also, in the mountainous western United States, most of the precipitation long-term stations are located in valley locations. Since snowfall increases rapidly with elevation in most areas of the mountainous west, (See Daly et al., 1994), area averaged precipitation over complex terrain tends to have systematic biases and needs orographic adjustment procedures.

Characterizing surface hydrological cycle requires adequate long-term record of some hydrological components, and such records consisting of the runoff and evaporation measurements in conjunction with soil moisture measurements are unfortunately lacking. Still, given a number of notable deficiencies that prevent a full qualitative closure of water and energy budgets from observations alone, model based four-dimensional data assimilation procedures and forecasts are required to attain more reliable results. Thus, useful alternatives to observe data include model-generated data, particularly when the models are driven by observed meteorological conditions. Maurer et al. (2002), for example, inferred evaporation, runoff, and soil moisture from precipitation and temperature measurements. There is an advantage of using model forecasts to describe the basin hydroclimatic processes. A model provides comprehensive hydroclimatological output and is a supplement to (but not replacement for) meager observations. For these reasons, current efforts to improve our understanding of the hydrological cycle remain focused on observations and modeling. On the other hand, understanding the hydrological cycle is a critical step on the road to improved modeling of seasonal and interannual variability of hydrologic components. Hydrological components can be used to assess the ability of a forecast model to estimate the energy and water balances on the river basin scales and to use observations of precipitation as evaluation data. For the most part models can conform qualitatively to available observations and each other, suggesting that perhaps we are at least closing the budget qualitatively through models and analyses.

As well be seen, in some situations, the evaluation has a critical impact on identifying surface processes that are poorly represented in the forecast model and thus lead to improvements in the modeling of the surface states and hydrological response, which in turn have a significant positive impact in numerical model prediction [e.g., Beljaars et al., 1996]. The detailed simulation of the water cycle and surface processes is a challenging task since it requires the skillful modeling of the subtle interplay between atmosphere/oceanic and land surface influences such as the complicating influences and coastal geometry. The higher resolution regional mesoscale models and multi-year assimilated and forecast datasets give the possibility of more accurately representing the effects of regional gradients associated with features such as coastlines, orography, land use, soil, and vegetation type.

The primary purpose of this study is to assess the Eta model for studies of the surface branch of the hydrological cycle over the western basins including Columbia and Colorado basin, and to provide further insight into the model prediction level on surface hydrological processes. The discussion has the objective of helping detect potential inaccuracies in the parameterizations and of providing an estimate of the reliability of the surface water cycle especially over complex terrain. The analysis is complemented with the inclusion of estimates from the observation-derived VIC model products, also described briefly in section 2.

A similar recent study for the subbasins of the Mississippi has been completed by Berbery et al (2003). Although the hydrometeorological behavior of the Mississippi River basin differs considerably from that of the western basins, some of the model issues are general in nature as later will be addressed. Others, in particular the errors in the representation of the solid precipitation processes in the model, are much important for the Columbia basin. From an evaluation of the 12-36h forecasts produced by the model over a period of June 1995-May2002, Berbery et al. (2003) found that precipitation estimates followed well the pattern seen in observations. They showed that, for the Mississippi basin as a whole, the monthly model precipitation from the 12-36 h forecast, when compared with gridded rainfall observations had a fairly small difference of 2%. For the western basins, not only precipitation observations but also upper-air observations used in the EDAS are less dense than they are over the Mississippi basin, and the

Columbia annual snowfall is much higher (and more difficult than rainfall to measure accurately), so that a high-resolution model may give useful estimates of precipitation at high spatial and temporal resolution. This positive Columbia basin-averaged precipitation bias is present in this study with Eta operational model of varying resolution, physics and data assimilation systems, and some of the causes and the model improvements under development will be discussed. Examination of the Eta model forecasts can highlight characteristic features of the water cycle and point out some of the serious issues that still affect the ability to develop adequate basin-scale budgets.

Basin-scale surface water budgets studies have been previously examined in a number of studies with limited data and models. This paper was inspired by the earlier work of Berbery (1999), Betts (1996,1998) and Roads (1994, 2000) but focused on different basins. Therefore, this research extends the surface water analysis of Berbery et al. (2003) to the western basins, and aims to produce a 'long term' regional climatology of the water cycles and relate them to land processes. The western basins have very complex orography and climate regime that makes it more challenging for any numerical model to predict correctly the water cycle and energy budgets. This expands our results and conclusions to include a significant different climate over a basin with significant cold season snowfall and a much larger runoff fraction. Recent attempts to quantifying of the hydrological cycle have been hampered by the quality of water balance requires accurate precipitation estimates. Accordingly, estimates of evaporation as a residual of the atmospheric vapor budget are also subject to uncertainties due to the difficulties of estimating the moisture flux convergence. Estimates of evaporation were produced using this estimate of convergence together with model and observed values of precipitation. Negative evaporation during the cold season was derived for the Columbia basin. Possible reasons for this bias include an underestimate of the observed precipitation and an overestimate moisture flux convergence. The estimates of precipitation and moisture flux convergence over the Columbia basin illustrate unsatisfactory result in achieving balance in water budget in the Eta model. The extent to which such imbalances are related to topography, resolution, and model forecast errors is still an open question. As a result, attempts to computing the atmospheric branch of the hydrological cycle of the Columbia basin have proved to be complex and more difficult to address. At current stage of higher resolution regional model and analysis system development, some aspects of the resolution problems are not fully overcome. Given the fact that these limitations in atmosphere hydrologic cycle, no attempts will be made to compute a balance of different components. Indeed, our interest is on documenting the all aspects of the surface hydrologic cycle, rather than trying to compute the atmospheric water budget.

The model data sets and observations used in this study are introduced in section 2. Section 3 performs analysis of observed precipitation and the model precipitation evaluation for the 8-yr period (June 1995-may 2003). Particularly, the implementation of soil moisture cycling in the EDAS in the mid-1998 led to significant progress in the quality of the Eta model products. With this in mind, the analysis of the basin-scale-average climatology of surface hydrologic components based on five years (June 1998-May 2003) of data is conducted in section 4. Finally, a summary and conclusions follow in section 5.

2. Eta model products and other datasets

The primary dataset for this study consists of the NCEP Eta meso-scale operational model forecasts for the period of 1995-2003 over North and Central America. They were initialized with the Eta Model's own four-dimensional data assimilation system, known as Eta Data Assimilation System (EDAS). The Eta Model has been executed at NCEP for several years, and EDAS was implemented operationally in April 1995 (Rogers et al. 1996). Since then, the Eta model has undergone significant changes, in particular in its physical packages and land surface model. Summaries of model changes during the period covered by this study and their expected effects on the model products can be found in Black et al. (1997), Betts et al. (1997), Berbery and Rasmusson (1999), Rogers et al. (2001a,b). Further details on significant changes to the NCEP Mesoscale Eta Analysis and Forecast System during May 1995-Dec 2001 are given in Berbery et al. (2003). Changes in physical parameterizations or initialization processes can produce changes in the model output. Among the more recent upgrades to the model, direct use of radiances from GOES satellites and the NOAA polar orbiting satellites in the 3DVAR analysis for the Eta implementation began in September 2000. Although the overall impact of the assimilation of radiances on precipitation over the contiguous U.S.

is small and positive, the regional breakdown shows a slightly greater positive impact in the western U.S. With improved treatment of satellite information by using radiances instead of retrievals, one would expect greater improvement in the western U.S, where is of central interest of this study. After 2001, the more important changes included modifications to the thermal conductivity over patchy and full snow cover (26-Feb-2002), and modifications to the land surface physics to avoid negative soil moisture availability under very dry soil conditions. The complete log of model changes is available at http://www.emc.ncep.noaa.gov/mmb/research/eta.log.html.

For past years, a systematic effort has been devoted to compute these hydrological variables through acquiring model output from NCEP's operational regional Eta model and its data assimilation system (EDAS), and currently the achieve has exceeded eight years (1995-2003). The 12-36 h Eta forecasts provide estimates of precipitation, evaporation, runoff, soil moisture, snow and other surface fluxes which are employed in this study to produce a 8-yr (June 1995-May 2003) climatology of the model precipitation and evaporation, and a 5-yr (June 1998-May 2003) climatology of the surface water cycle for the western basins.

Our study makes use of observational and observation-derived data sets to complement the Eta model forecasts. We have two sets of validation data. One is the daily gridded precipitation dataset prepared at NCEP's Climate Precipitation Center (CPC). We extracted the data for 1995-2003, and calculate a simple basin average from the 0.25° X 0.25° data that covers the entire continent of United States. It contains the daily gridded precipitation analysis using a modified Cressman scheme over the United States based on the CPC Unified Precipitation Data Set, which is a typical gauge-measured precipitation data set. The dataset and methodology employed to develop it, are explained by Higgin et al. (2000). This kind of Gauge estimates of precipitation without empirical corrections for orography or undercatch tend to be underestimated (Groisman and Leggates 1994). Some underestimate of precipitation may be obviously present in snow-dominated areas. Of particular concern is the Columbia River basin, a northwestern basin, which has significant frozen precipitation in winter, when the Higgins data will have a larger underestimate that may bring much uncertainty in estimating surface branch of water cycle.

The second dataset derives from the Variable Infiltration Capacity (VIC) model (Maurer et al. 2002). The Variable Infiltration Capacity (VIC) is a macroscale hydrologic model as described in detail by Liang et al. (1994; 1996). The VIC model balances both energy and water over a grid mesh, in this application at a 1/8-degree resolution, using a 3-hourly time step. In the second dataset, the model was forced by observed, or derived from observed meteorological data, giving approximately surface variables such as evaporation, runoff, soil moisture, and snow equivalent depth, and consequently enables us to provide all aspects of the surface hydrologic cycle. The raw raingauge based precipitation data were gridded to a 1/8degree grid and as described by Widmann and Bretherton (2000), the gridded daily precipitation were topography corrected with respect to altitude by applying the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1994). The algorithm, methodology, and a discussion of bias with respect to topography can be found in Daly et al. (1994). The use of PRISM in VIC model as bias adjustment method to account for orographic effects on precipitation results in more realistic representation of observed precipitation. Therefore, the PRISM model is important for developing better observations for precipitation in western United States. On this basis, a highly consistent 50-yr (January 1950-July 2000) dataset of surface variables that consists of observations (e.g., surface temperature) and derived data is developed by Maurer et al. (2002) and is believed to have each terms in surface balance well represented. To solve the difficulty in assessing model-predicted land-atmosphere exchange of moisture and energy due to the absence of comprehensive observations to which model prediction can be compared at the spatial and temporal resolutions at which the model operates, this derived dataset of land surface states and fluxes provides an opportunity as a reference for a variety of studies, especially where many observations are missing. Application of the VIC model for water and energy budget studies are described in Maurer et al. (2001a,b). Here, this dataset will be applied for an assessment of Eta model forecasts.

Note that Higgins precipitation data set does not account for orographic effects on precipitation and therefore does not include PRISM orographic adjustment procedure. The difference between the two data sets at monthly time scale basin-averaged over complex terrain such as the Columbia River basin is fairly large but relatively small in

Colorado basin (Fig. 2). Therefore, as has been described in Berbery et al. (2003), the discrepancies between our results and those of VIC results from this difference similar to those for the Mississippi basin, could have strong impacts on the entire numerical prediction system.

3. Model precipitation evaluation

Evaluation of the Eta model 12-36 h precipitation forecasts over the western United States was done for the 8-yr period covered in this study, June 1995-May 2003. To offer further insight, we provide intercomparison tests with the two observed precipitation estimates, thereby illustrating the influences of topography and precipitation regimes applying to each basin in the western United States.

3.1 Geographical distribution

Figure 2 depicts the mean annual observed, orography-corrected observed (VIC), and model forecast precipitation, as well as their differences over the western United States. As mentioned in previous section, VIC precipitation is topography corrected with respect to altitude, and thus can be regarded as the orography-corrected observed precipitation. Both observed precipitation estimates (Figs. 2a,b) are characterized by large values over the central Columbia basin, along the coastlines, over the western slopes of the Cascades and the Sierra Nevada. Maximum precipitation centered over the northwestern United States is also captured by the model precipitation forecast (Fig. 2c), although the model precipitation intensity lies between these two observation estimates. Spatially, the differences are larger in the mountainous west including the Columbia River basin where snowfalls are more prevalent and most region of California. These areas are especially prone to poor precipitation estimates due to the extensive large positive bias in gauge measurements of solid precipitation in Fig. 2(d). With topography correction made to the observed precipitation, the differences change into negative values in eastern half part of Columbia basin, while the positive values mostly centered in the western half part of the basin. A positive bias band-shape along the California coast still remain in Fig. 2(e). The model precipitation tends to differ more over the Columbia River basin than the Colorado basin, although both basin rivers originate from the Rocky Mountains. Away from the north and coast areas, the topography-related differences are less pronounced. Another differences arise in the southern coast of California as well as Colorado River basin, and a slightly dry model bias is observed over these regions.

Fig. 2(f) shows the difference between observed precipitation with and without PRISM correction and suggests that the gauge-only observed precipitation mostly underestimated the real precipitation over most western United States, due to its prevalent complex terrain. Again, the orography correction is evident over the slopes of the Cascades, the Rockies and the Sierra Nevada, but is small over flat areas. This character is of special significance in that it illustrates a large sensitivity of the monthly precipitation to the topography and northern cold weather conditions. We believe the current and even future precipitation evaluations over the Columbia basin may have such a similar problem.

Since the large positive biases appear in the northwestern region where orographic effects and snowfall weather are marked, the monthly and seasonal marches of difference between observed precipitation with and without PRISM are examined first in greater detail in the form of regional Hovmöller diagrams, for the longitudinal band between 125 ºW and 115 ºW at 48ºN (Fig. 3). The Hovmöller diagram depicts the differences of the two observed precipitation estimates are systematic (mostly during the cold months) and as large as 6-10 mm day^{-1}; a comparison with the topography profile reveals that the largest differences are found over the highest mountains and along the coastal areas. Note that there are almost no positive values, thus the CPC estimate is always lower than the VIC estimate.

Then the extent and annual evolution of the overprediction throughout the Columbia River basin in the Eta model are evaluated further. A comparison was performed in the same regional band between 125 ºW and 115 ºW at 48ºN. The results are summarized in the similar form of Hovmöller diagram (Fig. 4). Visual inspection of this figure reveals substantial variability with respect to year, along with large difference occurring along the coastal areas during winter months. The time series of the differences between observed and model forecast precipitation is shown in Fig. 4a, with an obvious decreasing trend in either dry or wet biases along the years. Much smaller biases are clearly seen after mid-1999. This trend illustrates the progressive reduction in forecast error over the Columbia basin resulting from model changes. These comparisons with observations on longer timescales are very encouraging for showing model precipitation forecast improvements. The precipitation bias also depicts a distinct seasonal variation (Fig. 4c), with maximum wet bias appearing during cold season and slightly dry bias during summer. Notable were a narrow band of dry bias occurring along the west coast and even a wider range of maximum wet bias nearby. This conforms that the core regions of maximum wet bias in the annual mean field (see Fig. 2d). However, the amplitude of differences is extremely large as the observed precipitation is replaced by topography-corrected precipitation (Fig. 4b and 4d). Although this correction leads to significant adjustment during cold season at the same areas, both figures show similar seasonal, location distribution of differences. The reduction in the bias still can be inferred although it not very clear in the Fig.4b.

3.2 Basin-scale interannual variability

The basin-scale area averaged time series of precipitation including uncorrected observations, VIC's corrected observations and Eta model forecasts, and their difference and RMSE (root mean square of error, here only for model forecast and uncorrected observed precipitation) are shown in Fig. 5 for the Columbia and Colorado basin, respectively. The time series of the precipitation are displayed to show the estimating uncertainties in quantifying the precipitation components in the surface hydrological cycle and the skill of the Eta model for simulating the surface branch of water cycle. After all, for each basin, the three curves of precipitation estimates track well as indicated in Fig 5a and Fig 5d. The model precipitation time series has a remarkable similarity to the observed time series, in particular, it seems to reproduce consistently the month-to-month variability.

Apparently in Fig. 5b and Fig. 5c, averaged over the Columbia basin, model estimates have high month-to-month variability and discrepancies in magnitude before 1999. From mid-1999 onwards, the observed and forecast precipitation show a closer agreement. Note that the observed precipitation does not show a significant year-to-year variation. The differences are significantly reduced in magnitude, and also the same is true for the Colorado basin (Fig. 5e and Fig. 5f.). These differences in model performance over different periods are assumed to reflect the impact of model changes on the precipitation estimation. These characteristics give the Eta model promise for providing more realistic surface water cycle over the western basins in the future.

In addition to month-to-month variability along the 8 years, the model shows the inter basin differences. Compare with the Columbia basin, the Colorado basin shows drier nature of climate, with a much weaker seasonal cycle and smaller magnitude of precipitation. The model has a tendency to overestimate the Columbia basin area-averaged precipitation but to underestimate the Colorado basin area averages. As display in Fig. 5b and 5c, the big positive difference and large RMSE mainly occur in the wintertime over the Columbia basin especially during the winters of 1995-1999. However, the Colorado basin is marked by the major discrepancies mostly occurring during the summer months (Fig. 5d and 5e). Two observation estimates have larger discrepancies over the Columbia basin while they tend to be much closer over the Colorado basin, implying considerable uncertainties in precipitation estimation over the Columbia basin especially during winter months.

3.3 Basin-scale mean annual cycle

a. Columbia basin

Fig. 6a shows the observed and the model-estimated mean annual cycle of monthly mean precipitation for the Columbia basin. In order to show the model performance in different periods, the 8-year climatology from June 1995 to May 2003 and 4-year climatology from June 1999 to May 2003 were displayed and compared. Here the VIC precipitation was not included for comparison due to its shorter period (June 1995-July 2000). Generally, the four curves are roughly close to each other, showing that a maximum in December-January and a decrease to minimum values in August. The Eta precipitation over the Columbia basin is larger than the observations almost the whole year. The largest difference occurs during winter when the basin has most of its precipitation falling during the winter. In an opposite manner, the difference is smallest during summer while the basin undergoes the least precipitation in a year. We believe this model peak near December-January is link to large fraction of winter snowfall in the mean annual cycle of precipitation. The Higgins observations from the rain gauges greatly underestimate snowfall in winter, and consequently, the model precipitation in winter is much larger than the observations for the Columbia basin. Overestimated precipitation in the northern basin is supported by studies of Betts (2000) and Berbery (1999). By contrast, the more recent four-year climatology depicts that the model precipitation bias was significantly smaller. This improvement occurs in the winter with the largest wet bias reduced from 1.5 mm day^{-1} to 0.75 mmday^{-1}.

For the purpose of better understanding the change in model performance, Fig.6b presents the mean annual cycle of the convective and large-scale components of the model precipitation during these two different periods. Examination of the model's partition of precipitation into convective and large-scale contribution reveals that on an annual basis, the ratio of large scale to convective component is about 5, which is remarkable orographically affected and cold climate feature of this basin. During the cold season, the most relevant precipitation is due to large-scale processes, which accounts for much of the total precipitation of Columbia basin. Another distinguishing characteristic of the Eta model is that the deficiencies in the northwest precipitation are associated with the large-scale component. Large-scale precipitation dominates over convective component during cold season into spring and is at a minimum during summer, but not zero. However, during summer, the convective component surpasses the large-scale precipitation, although it has a maximum during spring and a minimum even close to zero during winter. Thus, in conjunction with Figure 5, the wet bias in the model precipitation arises from either a deficit in observations or an excessive large-scale component or both. Moreover, the more current 4-year climatology of large-scale component is significantly reduced and leads to less excessive model precipitation most of the months except summer. In another words, the reduced magnitude of the forecast precipitation may be traced to the excessive large-scale component of precipitation over this basin. Both of these figures reveal an important indication that the improvement in model precipitation estimation over this basin mainly benefits from an overall improvement in the initial conditions because during 1999-2000 there were no corrections to the cold season land surface physics.

b. Colorado basin

Distinct from the Columbia basin, the Colorado basin has a two-peak mean annual cycle of precipitation (Fig. 7a), the first one during late winter probably due to snow storms over the mountains, and the second in mid to late summer associated with the onset of the monsoon season. The long term average shows that there is a deficit of precipitation all the year round (although larger during the summer months). Most of months within a year the precipitation is lower than 1.5 mm day^{-1}. The model has larger dry bias in the summer months as compared with observations. Here it is likely that the model gives the worse estimates of total summer precipitation. It is also found that significant different from the Columbia basin, the convective parameterization scheme is important in reducing underestimation of total precipitation during summertime over the Colorado River basin. The importance of convective parameterization scheme in Colorado basin is underscored in Fig. 7b. A decomposition of precipitation into large-scale and convective components has demonstrated that summer precipitation is strongly influenced by the convective processes. The large dry bias is associated with the convective component rather than large-scale component, which has been reduced and almost removed by the improved convective parameterization scheme. This impact has clearly shown for the more recent 4-year climatology. Thus, the changes in the convective parameterization scheme tend to enhance the convective precipitation component in summer and lead to model precipitation much closer to observations. Given the known dry bias in the Eta model over semiarid regions (Berbery and Rasmusson 1999), the results suggest an improvement in the forecasts quality. It also suggests that appropriate precipitation parameterization scheme applied over different regions will be a critical factor in improving the representation of the precipitation processes and thereby hydrological cycle in regional mesoscale models.

Although both basins have topography-related problems, which is prominent in winter months, the Eta model displays distinct performance in these two basins. The reason is that they are under significant climate regime. The dominance of convective processes over large-scale processes in Colorado basin is in sharp contrast to the dominance of large-scale over convective processes in Columbia basin, and this is closely related to the Eta model precipitation estimation performance. The model performed satisfactorily in Colorado basin but not the Columbia basin since the later one has large uncertainty in estimating real precipitation. It was discussed earlier the model tend to overestimate precipitation over the Columbia basin, but the real magnitude of the difference with the actual precipitation cannot be ascertained because of the large disparity between the two observation estimates. One of remaining problems in water budgets is the reliable estimation of basin-averaged precipitation. As a result, which precipitation estimates can provide more realistic precipitation is till a subject of debate. Still, more needs to be done to clarify the accuracy of theses results.

4. Land surface water budgets

We examine the ability of the Eta model to capture the spatial and temporal structure of the surface hydrological cycle by comparing the Eta model estimates to those of VIC model. Due to the nonexistence of the observations of many surface hydrological variables, especially like evaporation, snow water equivalent depth and soil moisture, etc., theses fields from Eta model are validated against VIC's estimates, which responds to the surface water balance equation driven by observed meteorological conditions.

4.1 Annual mean fields

Figure 8 depicts the 8-year annual mean fields of the Eta and VIC model evaporation over the western United States. VIC model evaporation (Fig. 8b) has larger values ranging between 1 and 3 mm day^{-1} mostly to the south and east, and in particularly includes the Columbia basin. The reminder of western United States has values typically between 0 and 1 mm day^{-1}. The Eta model 12-36 hr evaporation forecast shows similar regional-to-large scale features in Fig.8a with less detail and smoother gradients due to its coarser resolution. A slightly larger evaporation toward Oklahoma/Kansas and smaller evaporation near Oregon and the coastal areas of Washington State are observed. Remarkable also is that the Eta model has excess of evaporation over the Colorado basin, with a reasonable estimate of the large evaporation over the Columbia basin. An analysis of evaporation forecasts for the Mississippi basin using the same Eta model forecast products (Berbery et al., 2003), suggests that the difference between the model parameterized evaporation and VIC's is related to excessive bare soil evaporation in the

Eta model. Given the fact that VIC data set is not available after July 2000, differences between the two model results due to the difference in the averaging period may introduce uncertainties in the evaluation of evaporation estimates.

Figure 9 presents the annual mean fields related to the surface water balance as produced by the Eta model and VIC model parameterizations. In this case, the averages are performed for the period June 1998-May 2003, to avoid the earlier period when surface parameterizations had important changes; we still included many months after the July 2001 upgrade to have longer period (five complete years). It shows that main features of surface hydrological components are also well reproduced by the Eta model, although some difference arises regionally. The Eta-model produced water equivalent depth of accumulated snow presented in Fig. 9a shows a irregular latitudinal gradient with the Columbia basin, with values of about 10-50mm towards the north. Large values of snow accumulation exceeding 50 mm are observed over mountainous regions. The model has most aspects in common with the VIC model, like the maximum values over the mountainous regions, and even similar snow-free extent. However, the snow water equivalent depth in the VIC model is more intense and localized (Fig.9d). When focusing on basins, deep snow accumulation is dominant most of the Columbia basin and northern part of the Colorado basin.

Due to differences between the Eta's land surface model (Noah) and VIC's hydrologic model, soil moisture cannot be compared directly; therefore, the two fields were normalized to make them fit within their respective minimum and maximum ranges. The relative content of model-produced soil moisture is presented in Fig. 9b. The south basins including the southern portion of the Colorado basin are the driest while toward the north the Columbia basin is the one with highest soil moisture. Nevertheless, the Eta model reproduces the VIC model estimated maxima, including the regions within the Columbia basin despite some discrepancies with respect to maximum extent and magnitude. Some small-scale of maxima are noticed in the VIC model that are not well captured in the coarser resolution of the Eta model estimates (Fig. 9e). Note that while the Eta model grid spacing was changed several times and currently is 12 km, its output was interpolated to a 40 km×40 km grid, while VIC has a resolution of $0.125^{o}\times0.125^{o}$, which is four times higher than that of the Eta model output.

The Eta model forecast runoff is largest on the northwestern part of the Columbia basin (Fig. 9c). Runoff also achieves large values near the Rockies, the Central Valley in California. The similarity between the fields is encouraging: Deep runoff over high mountainous areas is clearly seen in both maps (Fig.9c and Fig. 9f). Runoff in the Columbia basin originates over the Rockies and Cascade Mountains, while that of the Colorado basin originates over the Rockies but also the Wasatch Mountains. Two runoff maximum bands exist: One is along northwest coastal cascade region; the other is along the Rocky mountain range, which extends to another smaller extent of maximum center toward the northeast of the Colorado basin. Similar to the previously discussed variables, the only differences still include maximum domain and magnitude. Of particular is the VIC model tends to produce patchy-like patterns, which have smaller extent of maximum values and smaller magnitude of runoff estimates. These features lead to smaller basin-scale area-averaged VIC model estimates as will be shown in next subsection.

In summary, the fields of precipitation, snow accumulation and runoff and even soil moisture share a common feature, that is, the locations of maximum centers of all estimates are very similar, implying they are closely related. This characteristic can be explained as stronger precipitation comes from heavier snowfall over the northern high mountainous regions (e.g. Rocky Mountain). Furthermore, the later melting of deep snow accumulation plus colder temperature and relative lower evaporation results in deep runoff and wet soil moisture in these same regions.

4.2. Basin-scale estimates

The mean annual cycle and time series of each of terms in the surface water cycle are evaluated for the Columbia basin and Colorado basin using the five complete years of data. The VIC estimates are included for model evaluation purposes (although the VIC data are available only until mid-2000).

Contrast of the Columbia basin evaporation climatology estimated by Eta model and VIC model, is shown in Fig. 10a. There appears to be a well-defined seasonal cycle. The magnitude of annual range in the Eta evaporation estimates is compatible to that of VIC model. On the other hand, large discrepancies are found in the phasing of the evaporation's seasonal cycle. The Eta model estimates is too high during spring but too low during autumn and much closer to the VIC model estimates during winter. This difference in the evaporation manifests itself in the Eta model calculations by shifting the peak two months earlier with respect to VIC model estimates.

Eta model runoff (Fig. 10b) achieves a maximum during spring and decays to quite low values in June and remains low values until the following winter. This result is evidenced by as observed winter snow accumulates in the northwest and western mountains, runoff peaks strongly in spring when snow melts. Large runoff discrepancies between Eta and VIC model shows that Eta runoff peaks at spring and is about two months ahead relative to VIC runoff. Its magnitude is quite large and is about twice as large as the VIC runoff.

Soil moisture of both models is again normalized for comparison purposes. The normalization is done here by taking the range between the minimum and maximum values corresponding to each model in the time series. Soil moisture (Fig. 10c) achieves a maximum in spring, about two months after the maximum in snow. Then it decays monotonically until October, due to the increasing evaporation (see Fig. 10a), and reduced precipitation during summer. The two curves show a very close well-defined mean annual cycle. It is relative wet during spring and relative dry during autumn. However, the VIC model tends to have later peak at June because the snow melting lasts longer time over this basin.

The Eta model's water equivalent of accumulated snow (Fig. 10d) has non-zero value starting in October, achieves a maximum of about 85mm in February and decays rapidly (snow melt) until April. The VIC model estimates shows a similar mean-annual cycle but have fairly large snow accumulations during mid winter until March. Unlike Eta model, the VIC model tends to have non-zero values during the warm season indicating the presence of not fully melted snow. Compared to VIC, the Eta model snow water equivalent depth has a negative bias during late winter and spring, and decays faster during spring.

The Colorado basin shows a somewhat similar surface hydrological structure but exhibits fairly weak annual mean cycle (Fig. 11). By summarizing, the area-averaged mean annual cycle and time series of all surface variables generally have a consistent evolution. There is a very close relationship among precipitation, snow accumulation, as well as runoff, and a peak with 1-2 month shift in components of the surface hydrological cycle appears to be a common feature of the Eta model with respect to VIC model. The Eta model captures the basic pattern of variability but tend to highly overestimate the magnitude in the surface hydrological variables, particularly runoff and soil moisture. Interannual variability includes natural variability and the effect of model changes; the time series of the basin averaged variables exhibit changes along the years that may be the result of changes in the model parameterization, but others occur consistently among all variables and observations suggesting a reflection of the natural variability.

4.3. The water balance terms

Table 1 summarizes by basin, for comparison with VIC model, the components in the 8-year and 5-year average of the Eta model surface hydrology, together with the corresponding Higgins precipitation for the two western basins. The observed precipitation with topography correction is significantly larger than the CPC observations, which implies the topography effect is more prominent for the Columbia than the Colorado basin since the difference between the two precipitation estimates is larger in the former than the latter. Over the Columbia basin, the VIC precipitation falls in between the observed precipitation and Eta model forecasts. Consequently, on the 8-year mean annual basis, the Eta estimate exceeds the CPC observed by 0.58 mm day^{-1}, which is a 34% overestimation, but only exceeds the VIC estimate by 2%. In contrast, the VIC precipitation of Colorado basin is slightly larger than both of the other two precipitation estimates but shows closer estimates. As shown in Table 1, the smaller bias of 0.10 mm day^{-1} with respect to CPC observed precipitation represents the precipitation is underestimated 12% by Eta model and 23% of bias with respect to VIC is underestimated. The reduction in Eta model biases for both basins on the 5-year climatology shows closer agreement with precipitation estimates. These results highlight the model improvement in precipitation computations.

On the 8-year basis, the mean annual cycle evaporation estimates results from both models agree closely with the Eta model estimates slightly greater than those of VIC model for both basins. The two estimates agree to within ~12% for Columbia basin and ~29% for Colorado basin. However, the difference is reduced to ~9% for the Columbia basin and 11% for the Colorado basin for the latter 5-yr period. There results are consistent with earlier studies that suggest that the Eta model has too high evaporation, despite corrections to its bare soil evaporation.

Based on the 5-yr average, both models have deep runoff over the Columbia basin but shallow runoff for the Colorado basin, with the Eta model providing considerable higher values of estimates in both basins. The snow water equivalent depth estimated from Eta model in Columbia basin is 49 mm smaller than VIC model, while it differs from VIC model by 8 mm larger in magnitude for the Colorado basin. However, both models produce deep snow accumulation and relative wet conditions toward the Columbia basin and thinner snow accumulation and dry conditions toward the Colorado basin.

Table 1. Annual mean surface water balance for western US basins

BASIN	Columbia		Colorado	
Period	8-yr	5-yr	8-yr	5-yr
P_{obs}	1.69	1.62	0.84	0.83
P_{vic}	2.23	1.99	0.96	0.94
P_{mod}	2.27	2.14	0.74	0.87
E_{vic}	1.20	1.19	0.89	0.93
E_{mod}	1.35	1.30	1.15	1.03
R_{vic}	1.03	0.86	0.14	0.14
R_{mod}	---	1.30	---	0.24
$SWE_{(vic)}$	80.64	76.04	7.55	1.98
$SWE_{(mod)}$	---	26.70	---	9.59

All units in mm day^{-1} except SWE that is in mm.

The progress in estimating the surface hydrologic cycle is inferred from Fig. 12 that presents the residual of the water balance equation. First, most areas are close to balance (no colors) with a residual that is less than 0.5 mm day^{-1} in magnitude. Imbalances with a positive residual are found over regions with high orography, while a negative residual is found along the northwest coast.

The area averaged residual for the Columbia basin (Fig. 12b) shows a well defined annual cycle with mostly positive values during spring and slightly negative values the rest of the year; when the effect of the annual cycle is removed (by performing a running mean; heavy line) it is clear that the residual term was at times as large as 2 mm day^{-1} before the year 2000, but it has since become smaller along the years. While not zero, since mid-2001 the values have remained of the order of 0.5 mm day^{-1} or less. Given the slow decreasing trend in the residuals, it is possible that there is no unique reason for these improvements, but it can be speculated that the continuous cycling of land and atmospheric states implemented in 1998 which slowly modified variables like soil moisture may have had an impact.

The Colorado basin (Fig. 12c) depicts a similar evolution of the residual term with a reduction of its magnitude from a maximum of about 1.3 mm day^{-1} before the year 2000 to slightly positive values in the more recent years. Unlike in the Columbia basin, the mean annual cycle (not shown) is not well defined, although relatively larger values are found in spring, summer and winter.

5. Summary and conclusions

This analysis of the main components of the surface hydrological cycle of the western basins in the United States provides a description of the basic physical aspects of the surface hydrological cycle as viewed from the Eta model, and confirms and extends the conclusions of our earlier study (Berbery et al., 2003).

Firstly, the Eta model is compared to two observed precipitation datasets: the first one is the gauge-based gridded precipitation developed at CPC; the second one, used by the VIC model, has a correction for orographic effects using the PRISM method. This correction increases the values of precipitation and consequently the CPC precipitation is systematically smaller than VIC's. In the case of the Mississippi basin, the differences were negligible (Berbery et al. 2003), but towards the west the overall differences (area average, time average) are of the order of 30% over the Columbia basin, and about 14% over the Colorado basin. These discrepancies between the two observed precipitation datasets pose large uncertainties on the entire estimation of the hydrologic cycle.

Secondly, the basin-scale monthly precipitation and evaporation estimated from the operational Eta model forecasts have been presented for the Columbia and Colorado basin for a 8-year period from June1995 to May 2003. The model shows a minimum precipitation in summer and a maximum in winter over the Columbia basin. The model precipitation is significant higher (by about 34%) than the uncorrected precipitation observations for this basin, although model and observed precipitation are well correlated on the basin scale and the correlation coefficient can be higher than 0.90. Our main verification, the Higgins et al. [2000] CPC precipitation data, shows that the model precipitation values generally exceed the observations especially during the winter months over this basin. This excessive precipitation over snow-dominated areas is a well-known bias (e.g. Berbery et al., 1999). The Eta model has reasonable annual mean cycle of convective precipitation in summer but an erroneous annual mean cycle of large-scale precipitation in winter. This error is probably linked to the model error in large-scale precipitation processes, which has large fraction to total precipitation during winter months. On the other hand, this may be partially due to an underestimation of observed precipitation.

Averaged over the Colorado basin, model precipitation shows a not well-defined annual cycle with less precipitation all the year round. It correlates quite well although may underestimate that observed typically by as much as 12%. However, the bias toward deficit precipitation may be contributed in part to the convective parameterization scheme.

Given substantial changes and upgrades on the Eta model during these years, we also see the promising improvement in reducing the biased precipitation as a critical component in the surface water cycle and the reduction of the water balance residual term.

Thirdly, Eta model products have been used to investigate the all aspects of the surface hydrological cycle at regional scale for the western United States. We have described the land surface hydrological processes for the western United States using Eta model forecasts. The data used in this study spans shorter period June 1998- May 2002. The VIC model estimates were used for evaluation of the Eta model. The mean annual pattern of each component bears encouraging resemblance to a pattern of relevant VIC model estimate, although regional discrepancies exist. Comparison of the forecasts of the components in the surface hydrological cycle with VIC model estimates shows similarity in location, shape, and scale of the patterns over the western basins. The large spatial variability in the annual mean fields is evident in both model estimates. It showed that the great complexity of those patterns in the northern part of the western United States including the Columbia basin is related to topographical features. It is believed that deep snowpack as product of large-scale precipitation processes contributes significantly to deep runoff and wet soil moisture.

Of particular interest was the evaluation of the Columbia and Colorado basin area-averaged annual cycle of the surface hydrological components. They have overall evolutions that reproduce those of VIC model, although the magnitude and timing of them do not match well the VIC model. Most of surface variables show a larger seasonal variability than that of the VIC model and peak one or two months earlier with respect to VIC model. All evaporation values generally showed compatible magnitude and the expected seasonal change, with maximum evaporation during warm season and a minimum evaporation during winter. In contrast, the model runoff, when compares to VIC model is too high on an annual basis. It has a large mean seasonal cycle: the basin shows a spring peak and a minimum in fall. The spring runoff peak in the model occurs, however, about two months earlier than the VIC's runoff peak estimated for the Columbia River basin. It was found that during the winter accumulation phase, the snow accumulation agrees reasonably well with the VIC's estimate; but, in spring, the model snow accumulation are too small. These model-produced differences are caused by the limitations of the physical parameterizations in the model. As a result, the magnitude of each component in the real hydrological cycle over western basins is still highly uncertain. Nonetheless, improved land surface parameterizations are needed to depict surface water processes and in particular, in seasonal snow accumulation, surface water, and runoff better.

These results are also remarkable as compared between the two basins. A notable aspect of mean season cycle over the Columbia basin is that it has the stronger mean annual cycle amplitude among all water cycle components. In sharp contrast, the much weaker mean annual cycle of runoff and soil moisture and even not well-defined annual cycle of soil moisture over the Colorado basin may be traced to the sparse precipitation all the year and semi-arid climate regime.

To summarize, this study is centered in the model's success and problems over the western basins that still need to be addressed to produce reliable estimates of the hydrological budget. Characterizing all aspects of the hydrological cycle accurately from observations and model estimation is a difficult task, in that there remain substantial uncertainties in precipitation evaluation, model resolution and parameterization. Preliminary results indicate that the Eta model is capable of capturing general features of mean annual cycle of surface water and energy balance over the western basins. Results from this study are distinct form that of the earlier study [Berbery et al., 2003] which focused on Mississippi basin. They show significant different features in water and energy budgets due to different climate regimes over these western basins. It reveals that total different magnitude and phase of the Eta model-based mean annual water and energy cycle over the Columbia basin as compared to the Mississippi basin. We emphasis the performance of Eta model are basin dependent. In both cases, the results are not systematic in the sense that they vary from basin to basin. The above results highlight the potential factors in determining the performance of the Eta model on different basins. Not surprisingly, better performance in precipitation estimation over the Mississippi basin but poorer over the western basin are possibly arising from: 1) the different climatic regimes; 2) different observational environments; 3) significant different physiography which has different requirements on model resolution. The model may have more difficulties in estimation of the hydrological cycle in regions like the Columbia basin, which has larger annual variations, complex terrain and sparsely sampled observational data since this situation may bring many uncertainties in the model. The presence of complex physiography and precipitation regime for each basin may make the estimation of the hydrological cycle more difficult, and how such factors will affect the model simulation is not well acknowledged. Changes to the parameterization of precipitation processes and surface processes are expected to improve the precipitation prediction, although it is not clear how it may have affected each basin in particular. Still, how such factors will affect the model parameterizations is poorly understood.

Finally, it is important to understand the limitations of our study. One should also note that, the shorter compatible period of the VIC model record makes it difficult to assess the Eta model. These tentative conclusions will be further investigated as the Eta regional reanalysis data become available. It is expected that NCEP Regional Reanalysis will help identify better the structure and intensity of surface hydrological cycles over the western basins. We believe that an effort to produce a longer period of Eta regional reanalysis dataset should allow much improved description of the surface water budgets.

References

Adam, J. C., and D. L. Lettenmaier, 2003: Adjustment of global gridded precipitation for systematic bias. *J. Geophys. Res.*, **108(D9)**, 1-14.

Berbery, E. H., E. M. Rasmusson, and K. E. Mitchell, 1996: Studies of North American continental scale hydrology using Eta Model forecast products. *J. Geophys. Res.*, **101(D3)**, 7305-7319.

————, and ————, 1999: Mississippi moisture budgets on regional scales. *Mon. Wea. Rev.*, **127**, 2654-2673.

————, K. E. Mitchell, S. Benjamin, T. Smirnova, H. Ritchie, R. Hogue, and E. Radeva, 1999: Assessment of land-surface energy budgets from regional and global models. *J. Geophys. Res.*, **104(D6)**, 19,329-19,348.

————, Y. Luo, K. E. Mitchell, and A. K. Betts, 2003: Eta model-estimated land surface processes and the hydrologic cycle of the Mississippi basin. *J. Geophys. Res.*, **108(D22)**, 8852, doi:10.1029/2002JD003192.

Betts, A. K., F. Chen, K. E. Mitchell, and Z. I. Janjić , 1997: Assessment of the Land surface and boundary layer models in the two operational versions of the NCEP Eta model using FIFE data. *Mon. Wea. Rev.*, **125**, 2896-2916.

————, and P. Viterbo, 2000: Hydrological budgets and surface energy balance of seven subbasins of the Mackenzie River from the ECMWF model. *J. Hydrometeorology*, **1**, 47-60.

Black, T. L., 1994: The new NMC Mesoscale Eta model: Description and forecast examples. *Wea. Forecasting*, **9**, 265-278.

Chen, F., K. Mitchell, J. Schaake, Y. Xue, H. Pan, V. Koren, Q. Duan, and A. K. Betts, 1996: Modeling of land-surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res.*, **101**, 7521-7268.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer, 2004, Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. *Climatic Change*, *in press*.

Daly, C., R. P. Neilson, and D. L. Philips, 1994: a statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Meteor*., **33**, 140-158.

Groisman P. Y., and D. R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc*., **75**, 215-227.

Higgins, R. W., W. Shi, E. Yarosh, and R. Joice, 2000: Improved United States quality control system and analysis. NCEP/Climate Prediction Center ATLAS No 7, U. S. Department of Commerce, NOAA/NWS, 2000. [Available on line at http://www.cpc.ncep.gov/research_papers/ncep_cpc_atlas/7/index.html].

Leung, L. R., and S. J. Ghan, 1998: Parameterizing subgrid orographic precipitation and surface cover in climate models. *Mon. Wea. Rev*., **126**, 3271-3291.

Maurer, E. P., G. M. O'Donnell, D. P. Lettenmaier, and J. O. Roads, 2001: Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE Reanalyses using an Off-line Hydrologic Model. *J. Geophys. Res.,* **106(D16)**, 17,841-17,862.

————, A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen, 2002: A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United State. *J. Climate*, **15**, 3237-3251.

Payne, J. T., A. W. Wood, A. F. Hamlet, R. N. Palmer, and D. P. Lettenmaier, 2004: Mitigating the effects of climate change on the water resources of the Columbia River basin, *Climatic Change, in press*.

Pulwarty, R. S., and K. T. Redmond, 1997: Climate and Salmon Restoration in the Columbia River Basin: The Role and Usability of Seasonal Forecasts. *Bull. Amer. Meteor. Soc*, **78**, 381-397.

Roads, J. O., S. C. Chen, A. K. Guetter, and K. P. Georgakakos, 1994: Large-scale aspects of the United States hydrologic cycle. *Bull. Amer. Meteor. Soc*., **75**, 1589-1610.

Rogers, E., T. L. Black, D. G. Deaven, and G. J. DiMego, 1996: Changes to the operational early Eta analysis/forecast system at the National Centers for Environmental Prediction. *Wea. Forecasting*, **11**, 391-413.

————, ————, W. Collins, G. Manikin, F. Mesinger, D. Parrish, and G. DiMego, 2001a: Changes to the NCEP Meso Eta analysis and forecast system:

Assimilation of satellite radiances and increase in resolution. NWS/NOAA Tech. Proc. Bull., 473. [Available on line at http://www.nws.noaa.gov/om/tpb/inddraft.htm].

————, M. Ek, Y. Lin, K. Mitchell, D. Parrish, and G. DiMego, 2001b: Changes to the NCEP Meso Eta analysis and forecast system : Assimilation of observed precipitation, upgrades to land-surface physics, modified 3DVAR analysis. NWS/NOAA Tech. Proc. Bull., 479. [Available on line at http://www.nws.noaa.gov/om/tpb/inddraft.htm].

Widmann, M., and C.S. Bretherton, 2000: Validation of mesoscale precipitation in the NCEP reanalysis using a new grid-cell data set for the northwestern United States, *J. Climate,* **13**, 1936–1950.

Figure Captions

Figure 1: The topography of the western United States and the location of the Columbia and Colorado basins. (Courtesy Ernesto H. Berbery)

Figure 2: June 1995-May 2003 annual mean fields of (a) observed precipitation; (b) observed precipitation with PRISM correction (VIC precipitation); (c) Eta model 12-36 h forecast precipitation; (d) difference between (a) and (c); (e) difference between (b) and (c); (f) difference between (a) and (b).

Figure. 3: Hovmöller diagram of the differences between observed precipitation and observed precipitation corrected with PRISM at 48º N for June 1995-July 2000. Counter interval is 2 mm day^{-1}. The topographic profile at 48º N is included for reference.

Figure 4: Hovmöller diagrams of (a) time series and (b) mean annual cycle of the differences between the Eta model forecasts and observed precipitation at 48ºN for June 1995- May 2003. (c), (d) same as (a), (b) but with the observed precipitation corrected with PRISM. Counter interval is 2 mm day^{-1} for (a,b) but 1 mm day^{-1} for (c,d). (The blank band indicates missing data due to the fire destruction of NCEP's computer in 1999.)

Figure 5: June 1995-May 2003 Columbia basin area-averaged time series of (a) Eta model precipitation, VIC precipitation, and observed precipitation; (b) their difference; and (c) the model's RMSE. (d)-(f)same as (a)-(c) but for the Colorado basin. Units are mm day^{-1}.

Figure 6: (a) Mean annual cycle of the Columbia basin area-averaged model and observed precipitation during 1995-2003 and 1999-2003; (b) Mean annual cycle of the Columbia basin-averaged Eta model precipitation components: large-scale (Pls) and convective (Pcon) during 1995-2003, and 1999-2003.

Figure 7: Same as Figure 6 but for the Colorado basin.

Figure 8: June 1995-May 2003 annual mean fields of (a) Eta model parameterized evaporation, and (b) VIC estimated evaporation.

Figure 9: June 1998-May 2003 annual mean fields of (a) water equivalent of accumulated snow depth, (b) normalized soil moisture for the 0-200cm layer, (c) runoff. All fields are estimated from the Eta model 12-36 h forecasts. (d)-(f) same as (a)-(c), but for the VIC model.

Figure 10: June 1998-May 2003 Columbia basin area-averaged mean-annual cycle and time series of evaporation (a,b), runoff (c,d), normalized soil moisture (e,f), and water equivalent of accumulated snow depth (g,h).

Figure 11: Same as Figure 10 but for the Colorado basin.

Figure 12: The residual term of the water balance equation estimated from the Eta model; (a) mean field, (b) area average for the Columbia basin, (c) area average for the Colorado basin. The heavy line in (b) and (c) represents a running mean to remove the annual cycle.

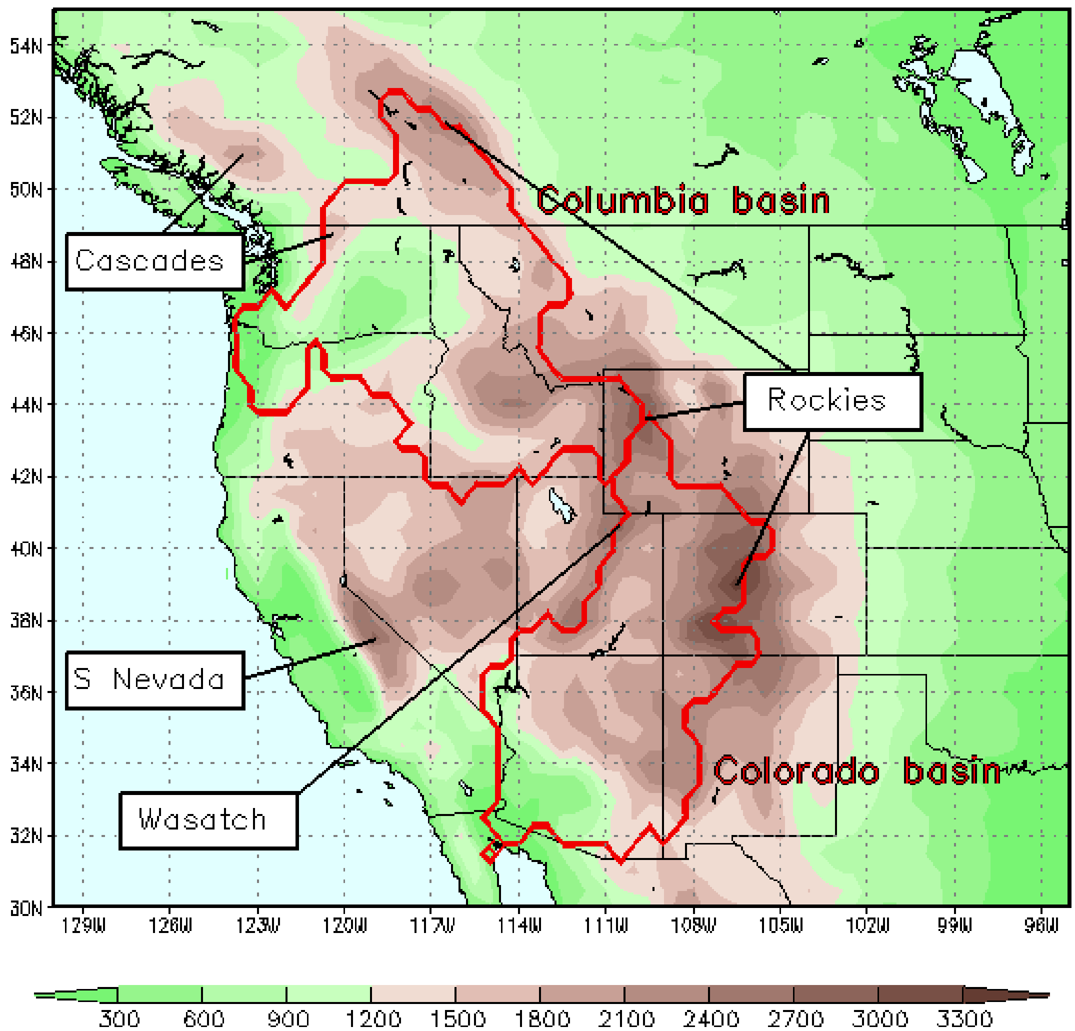

Fig. 1. The topography of the western United States and the location of the Columbia and Colorado basins. (Courtesy Ernesto H. Berbery)

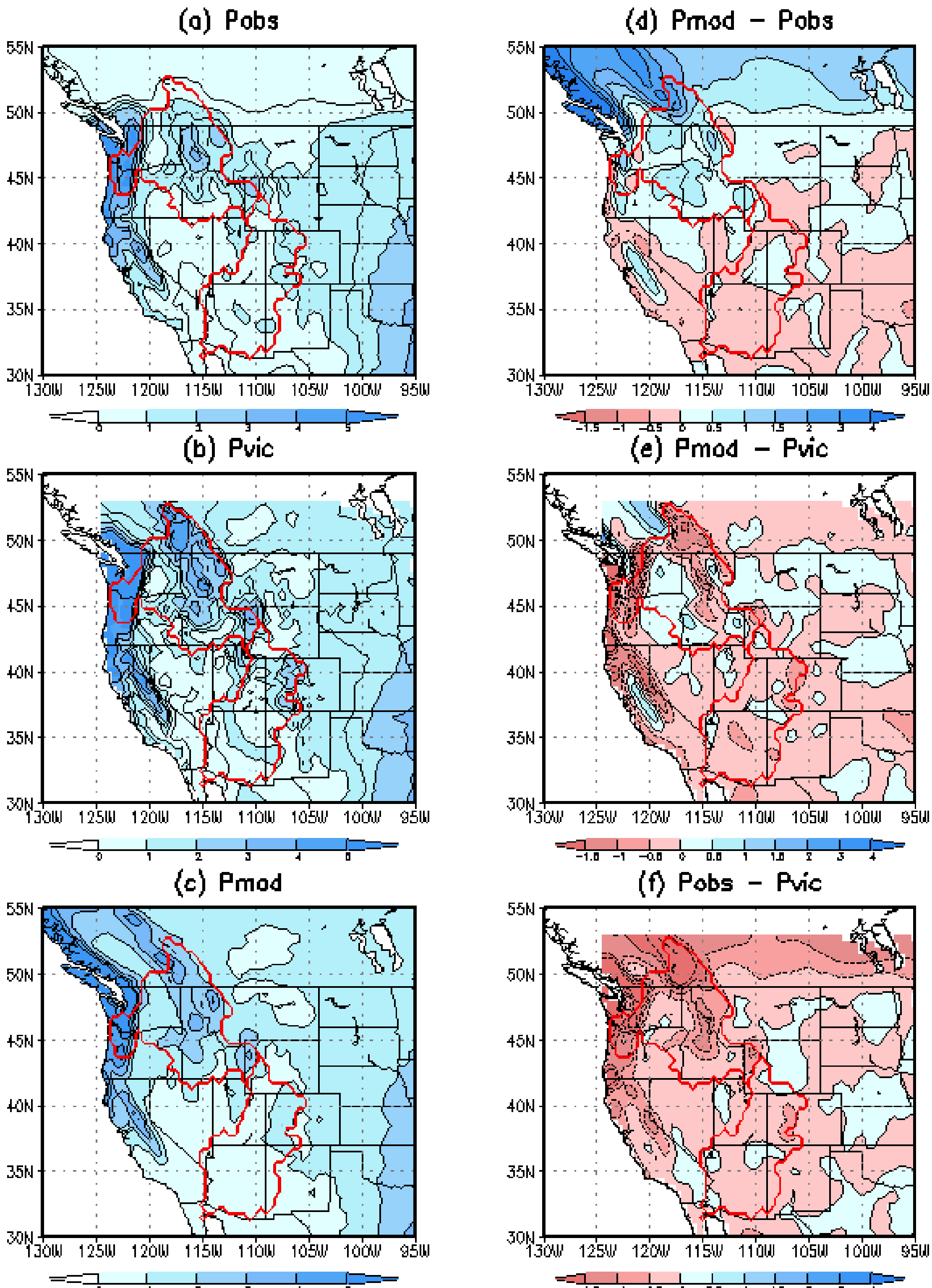

Fig. 2. June 1995-May 2003 annual mean fields of (a) observed precipitation; (b) observed precipitation with PRISM correction (VIC precipitation); (c) Eta model 12-36 h forecast precipitation; (d) difference between (a) and (c); (e) difference between (b) and (c); (f) difference between (a) and (b).

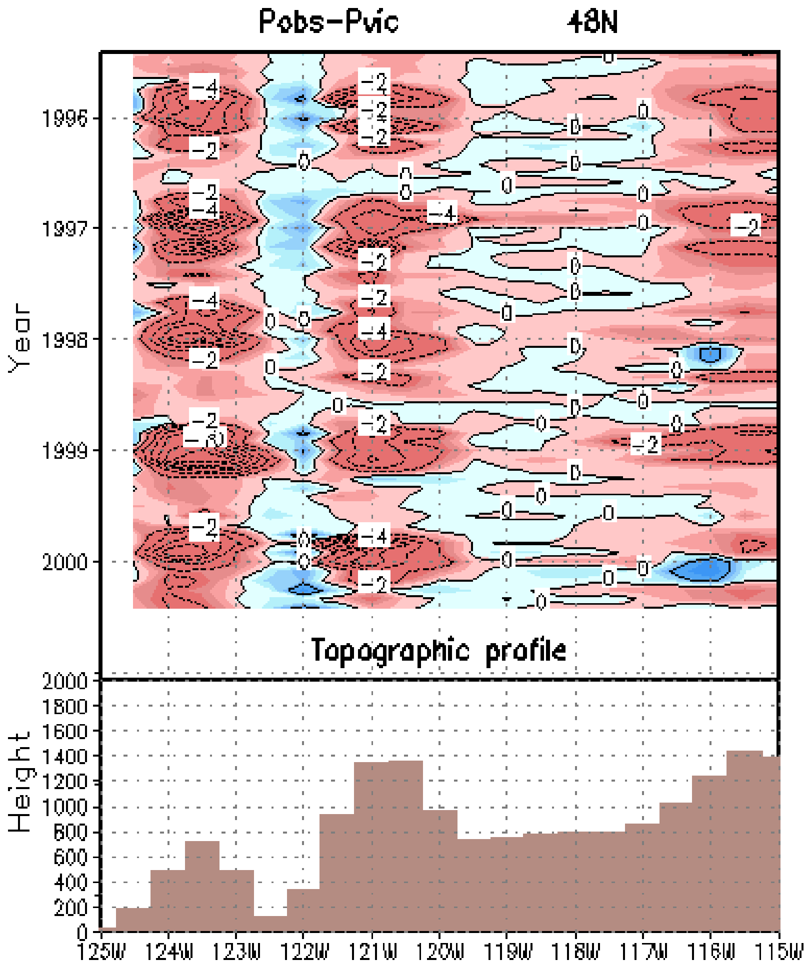

Fig. 3. Hovmöller diagram of the differences between observed precipitation and observed precipitation corrected with PRISM at 48º N for June 1995-July 2000. Counter interval is 2 mm day^{-1}. The topographic profile at 48º N is included for reference.

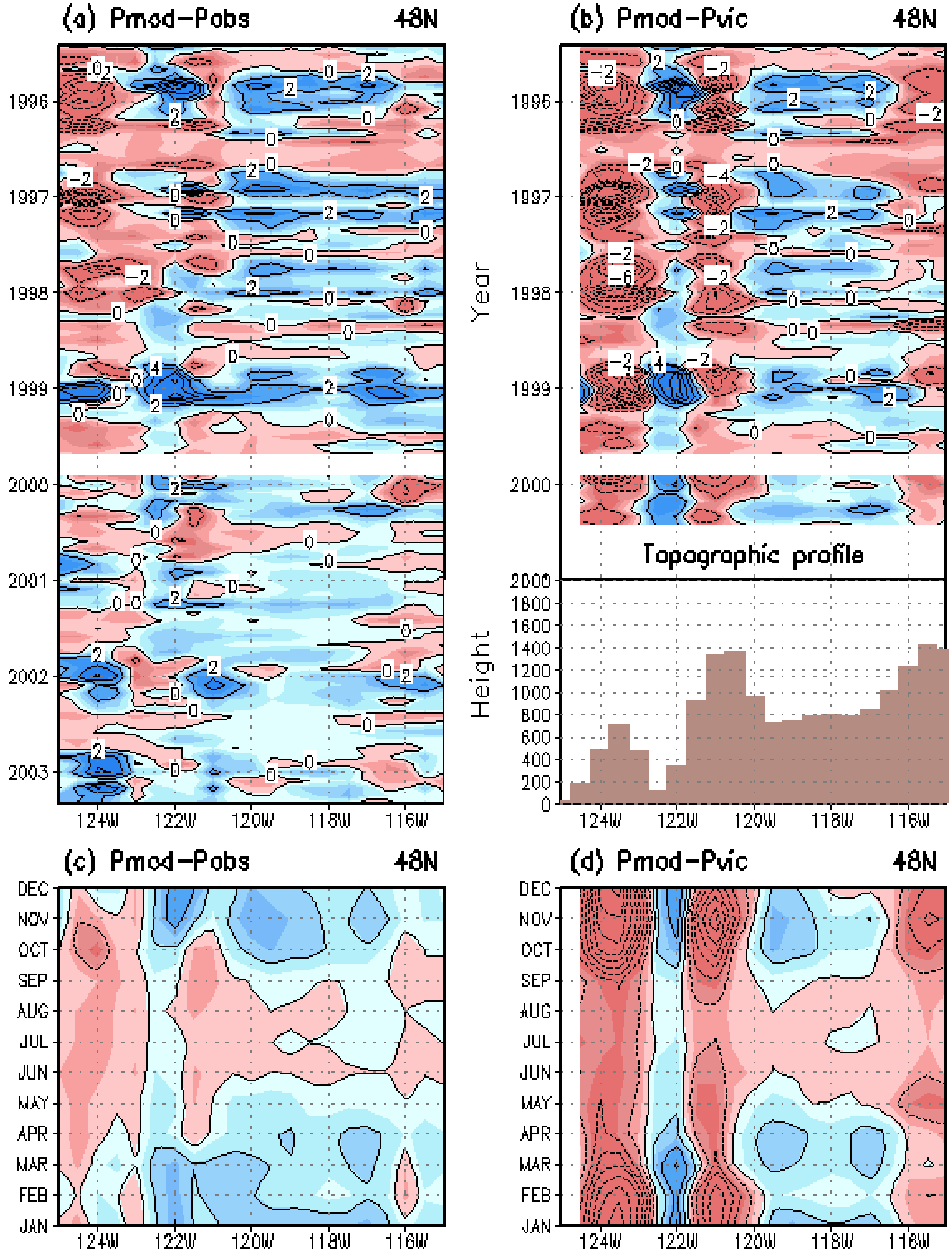

Figure 4

Fig. 4. Hovmöller diagrams of (a) time series and (b) mean annual cycle of the differences between the Eta model forecasts and observed precipitation at 48ºN for June 1995- May 2003. (c), (d) same as (a), (b) but with the observed precipitation corrected with PRISM. Counter interval is 2 mm day^{-1} for (a,b) but 1 mm day^{-1} for (c,d). (The blank band indicates missing data due to the fire destruction of NCEP's computer in 1999.)

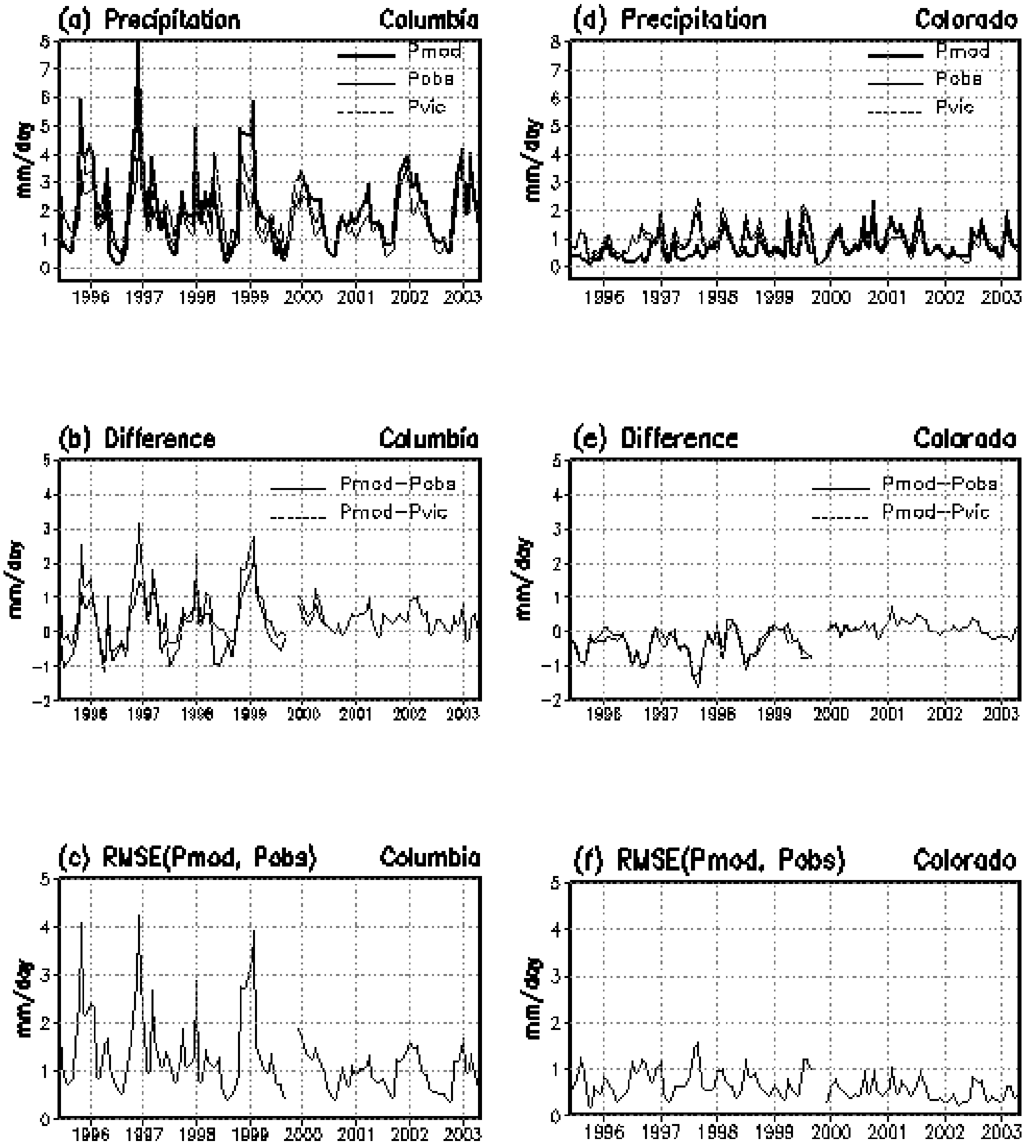

Fig. 5. June 1995-May 2003 Columbia basin area-averaged time series of (a) Eta model precipitation, VIC precipitation, and observed precipitation; (b) their difference; and (c) the model's RMSE. (d)-(f)same as (a)-(c) but for the Colorado basin. Units are mm day^{-1}

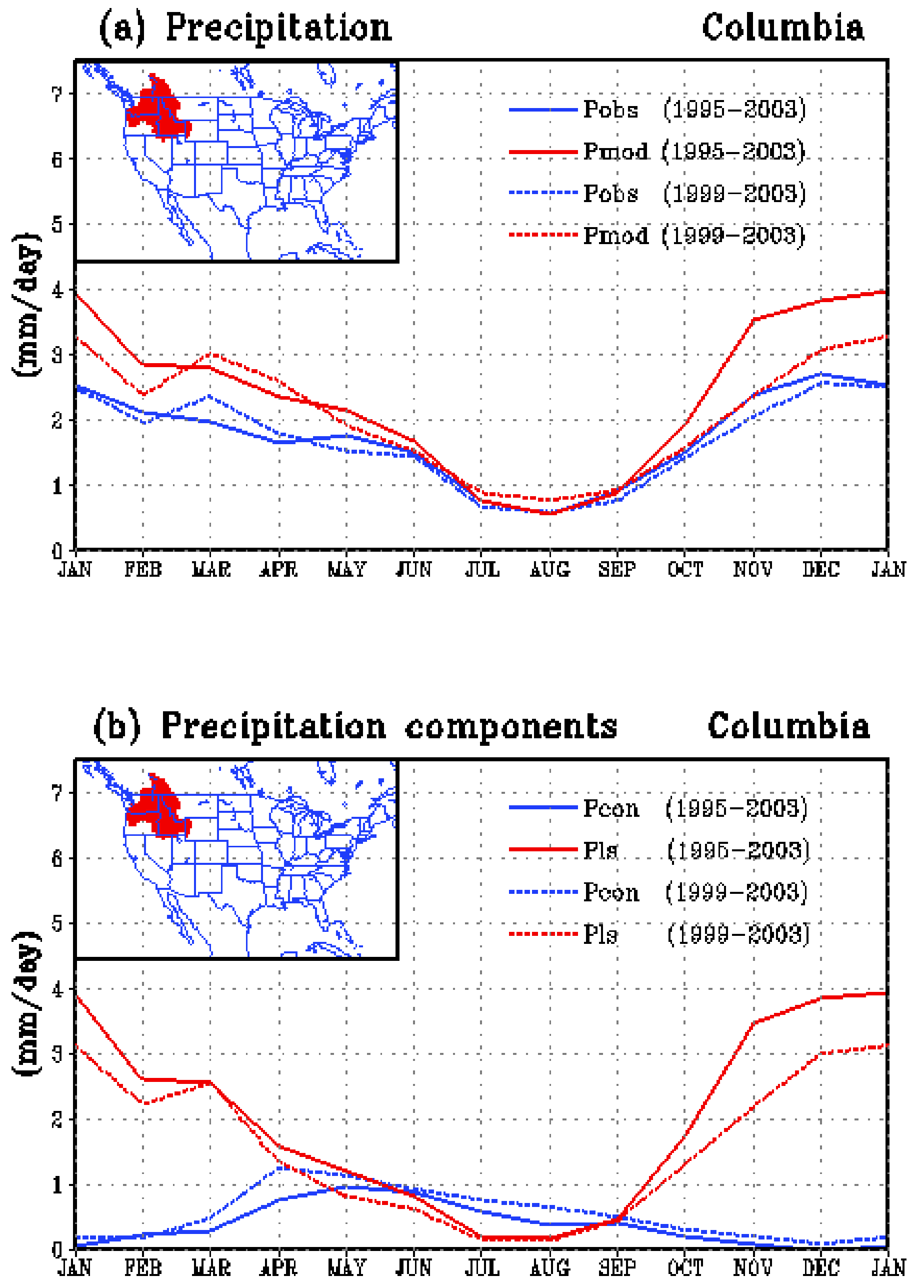

Fig. 6. (a) Mean annual cycle of the Columbia basin area-averaged model and observed precipitation during 1995-2003 and 1999-2003; (b) Mean annual cycle of the Columbia basin-averaged Eta model precipitation components: large-scale (Pls) and convective (Pcon) during 1995-2003, and 1999-2003.

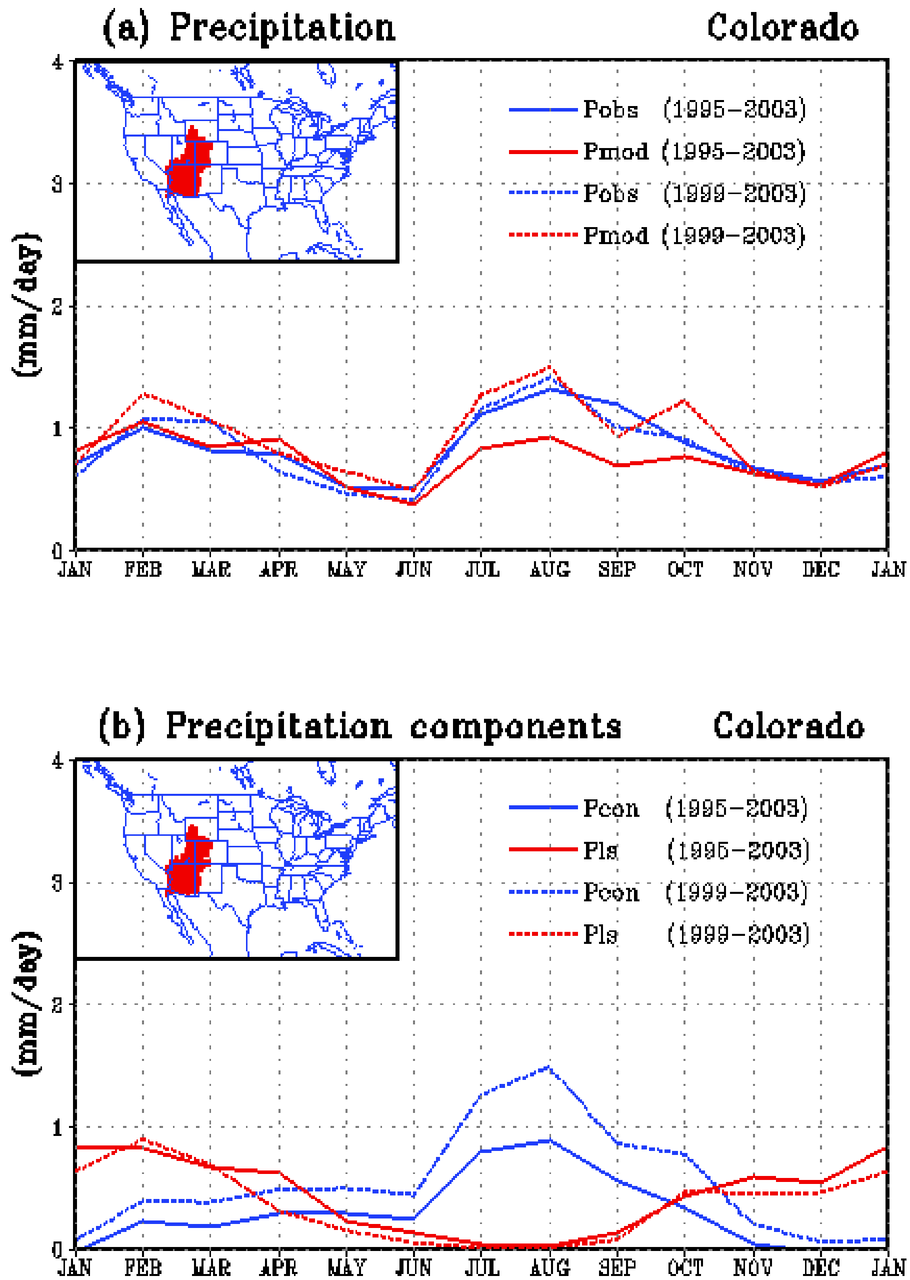

Fig. 7. Same as Fig. 6 but for the Colorado basin.

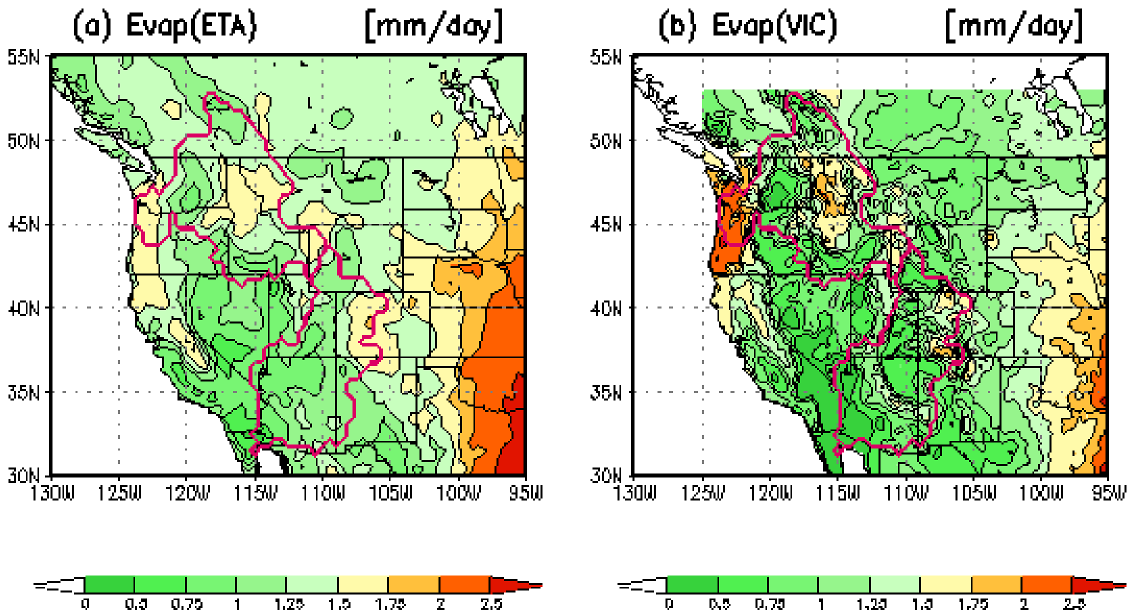

Fig. 8. June 1995-May 2003 annual mean fields of (a) Eta model parameterized evaporation, and (b) VIC estimated evaporation.

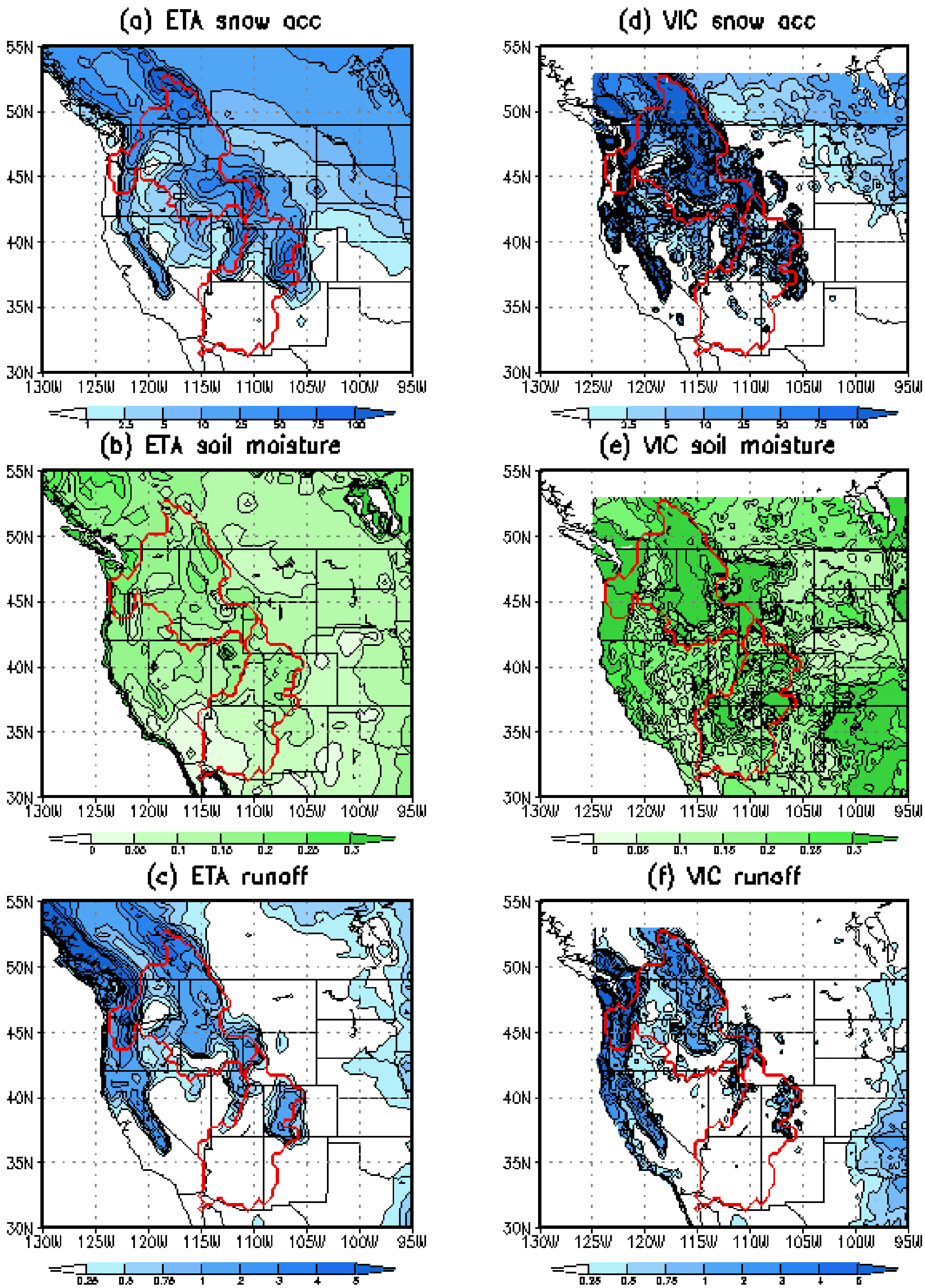

Fig. 9. June 1998-May 2003 annual mean fields of (a) water equivalent of accumulated snow depth, (b) normalized soil moisture for the 0-200cm layer, (c) runoff. All fields are estimated from the Eta model 12-36 h forecasts. (d)-(f) same as (a)-(c), but for the VIC model.

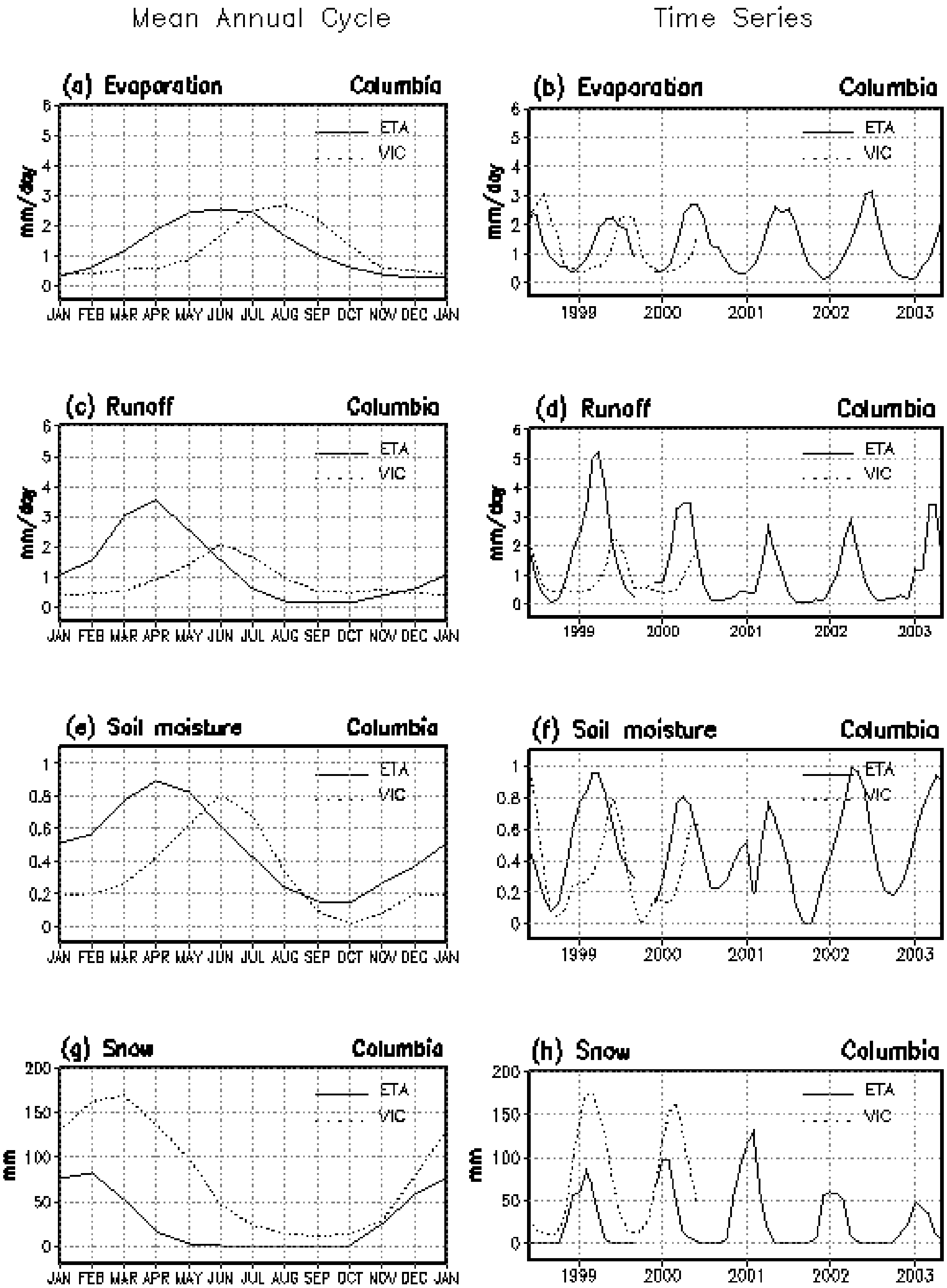

Fig. 10. June 1998-May 2003 Columbia basin area-averaged mean-annual cycle and time series of evaporation (a,b), runoff (c,d), normalized soil moisture (e,f), and water equivalent of accumulated snow depth (g,h).

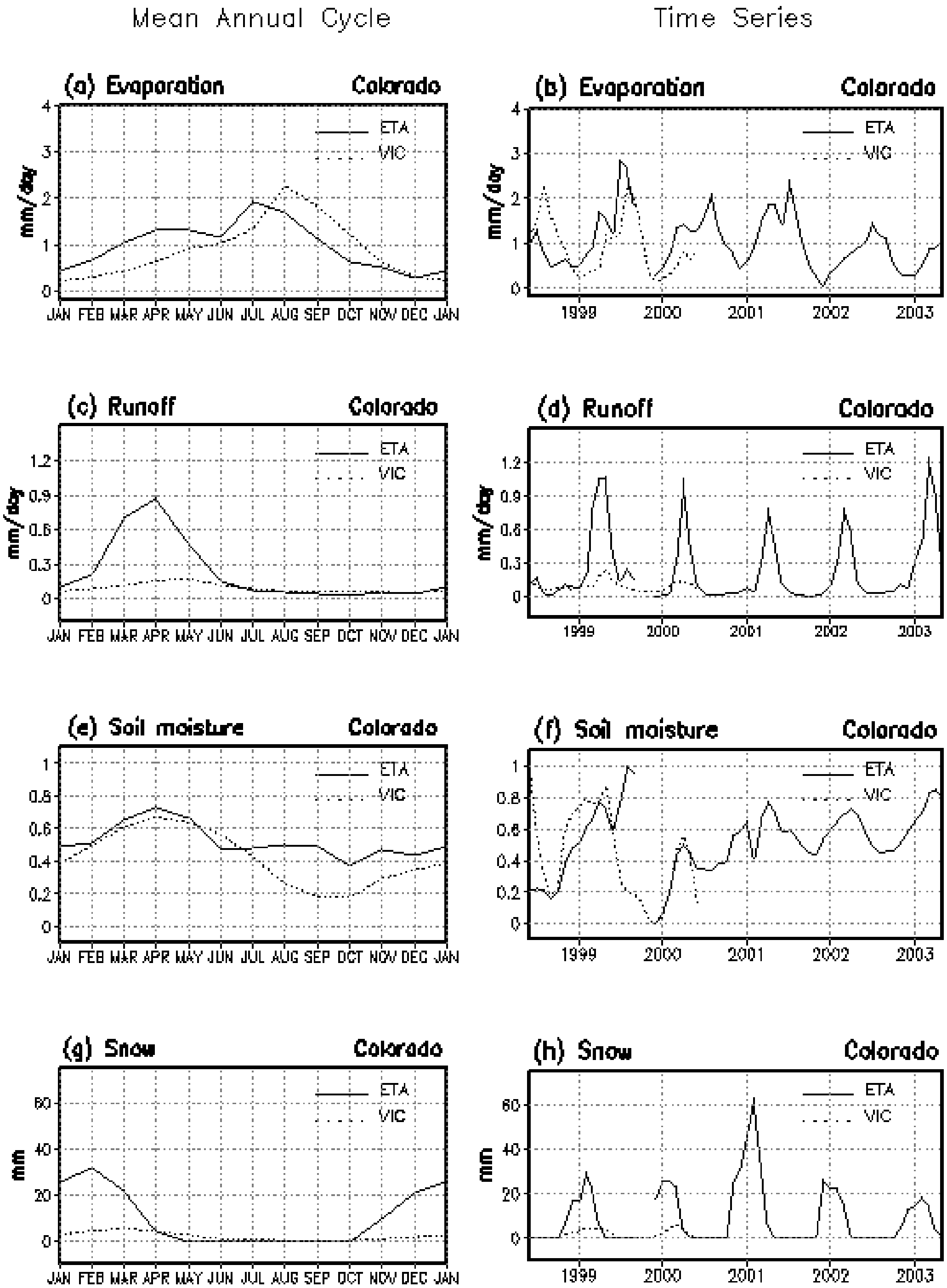

Fig. 11. Same as Fig. 10 but for the Colorado basin.

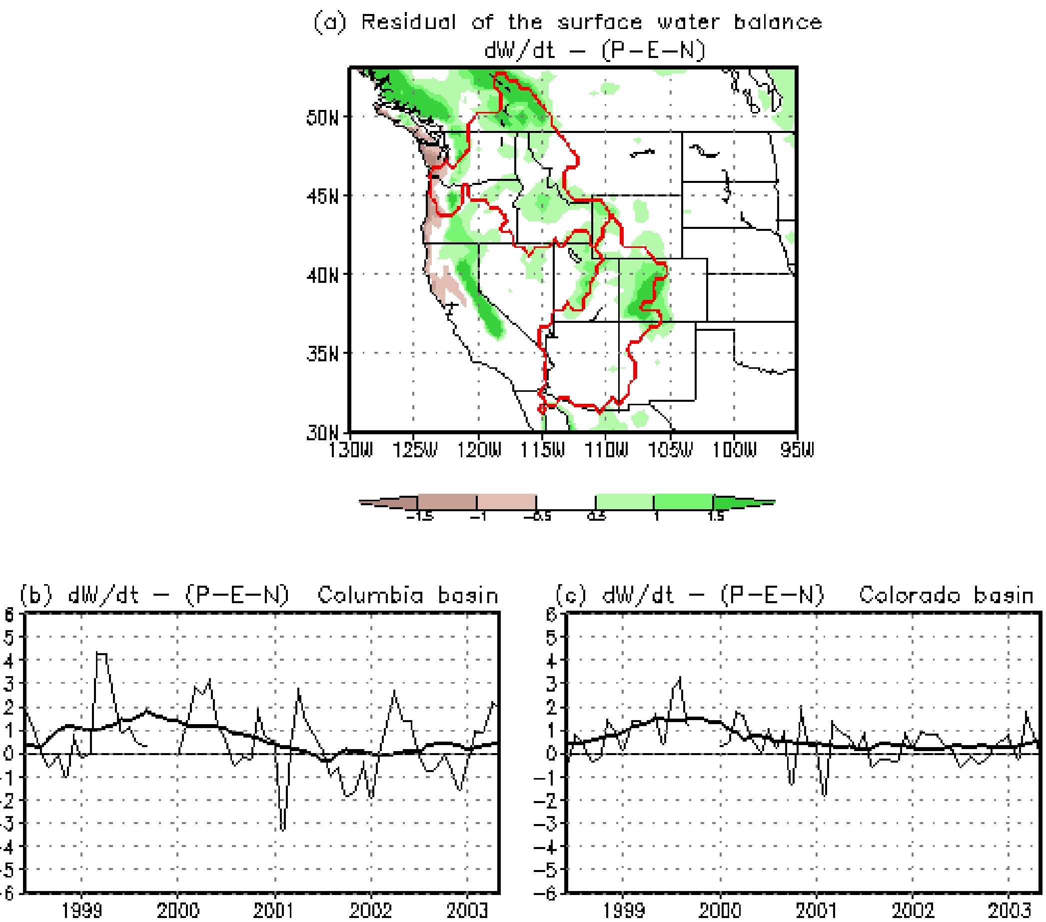

Fig. 12. The residual term of the water balance equation estimated from the Eta model; (a) mean field, (b) area average for the Columbia basin, (c) area average for the Colorado basin. The heavy line in (b) and (c) represents a running mean to remove the annual cycle.