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**Abstract**
We evaluated the precipitation climatology of the Intermountain Region (IR) as generated by the six regional climate models of the North American Regional Climate Change Assessment Program (NARCCAP). A complex combination of the precipitation annual and semiannual cycles with their different phases form four major climate regimes over the IR. Each model produces systematic biases in the central IR where these different climate regimes meet. The simulated annual cycles are universally too strong, and the winter precipitation is too large. On the other hand, the semiannual cycles are relatively well produced. The strong annual cycles and the excess winter precipitation obscure the signals of spring/summer precipitation and may have led to false signals of the El Niño-Southern Oscillation (ENSO) found in the central IR. Therefore, caution is advised when interpreting the simulated NARCCAP precipitation for the IR.

**Keywords**
Intermountain, Precipitation, Climatology

**Disciplines**
Agronomy and Crop Sciences | Climate

**Comments**
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# Evaluation of precipitation in the Intermountain Region as simulated by the NARCCAP regional climate models

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## 1. Introduction

[2] High-resolution modeling is important to regional climate research, and particularly so for areas with complex terrain, such as the Intermountain Region (IR) of the western United States between the Cascade-Sierra range and the Rocky Mountains (Figure 1a). Seasonal variations of precipitation, an important indication for evaluation of climate simulations [*Boyle*, 1998], are often portrayed in terms of the annual and semiannual cycles through harmonic analysis. Early studies [e.g., *Hsu and Wallace*, 1976; *Kirkyla and Hameed*, 1989] indicated that seasonal precipitation of the IR is characterized by annual and semiannual cycles whose timing varies across the region. The phase of the annual cycle changes by six months going from east to west across the Rockies, while the semiannual cycle changes phase from north to south [cf. *Hsu and Wallace*, 1976, Figures 8 and 9]. The combination of these seasonal cycles produces four major precipitation regimes that meet in the central IR near Utah. Furthermore, the annual cycle can be decomposed into a winter-summer mode and a spring-fall mode by use of principal component (PC) analysis [*Heddinghaus and Krueger*, 1981]. Over the U.S., the spring-fall mode of the hydrological cycle has been found to be critical, as it leads to the large late-spring rainfall in the Great Plains [*Wang and Chen*, 2009].

[3] General circulation models (GCMs) do not simulate well the semiannual cycle of precipitation [*Boyle*, 1998]. The spring-fall mode and the semiannual cycle remain largely unrealistic in today's GCM climate simulations (T.-C. Chen et al., Possible remote forcing for the U.S. Great Plains droughts, submitted to *Journal of Climate*, 2009). Additional complexity arising from interaction between atmospheric circulation and orography, as is encountered in the IR, likely amplify such model deficiencies. Regional climate models (RCMs) can produce more realistic precipitation than GCMs [*Leung et al.*, 2003a, 2003b], particularly in regions having topographically driven precipitation such as the IR. Herein we examine how accurately RCMs simulate seasonal and interannual variabilities of precipitation in the IR. We analyzed the precipitation climatology produced by six RCMs participating in the North American Regional Climate Change Assessment Program (NARCCAP), an international program to study climate variabilities/impacts over North America and to project future climate through the application of an ensemble of RCMs (L. O. Mearns et al., North American Regional Climate Change Assessment Program: An overview, submitted to *Eos, Transactions, American Geophysical Union,* 2009). The present study evaluates the ability of NARCCAP RCMs to replicate important features of precipitation variability in the IR.

## 2. Data and Results

[4] The NARCCAP engages six RCMs (CRCM, ECPC, MM5I, RCM3, WRFP and HRM3, abbreviations explained in Figure 1) that are run at a 50 km horizontal resolution and driven by the lateral boundary conditions set by the NCEP/DOE Reanalysis II data (R-2) [*Kanamitsu et al.*, 2002] for the period of 1979–2004. The NARCCAP website (http://www.narccap.ucar.edu) provides detailed information of the project and the RCM characteristics. Observations were obtained from the gauge-based precipitation of the University of Delaware (UDel) [*Legates and Willmott*, 1990] at a 0.5° resolution, as well as the North American Regional Reanalysis (NARR) [*Mesinger et al.*, 2006] which assimilates observed gauge precipitation analyses at a 32 km resolution. These are referred to simply as the observations in the text that follows.

[5] As shown in Figure 1a, upper-level flows encounter four major mountain ranges: (1) the Cascade Range, (2) the Bitterroot Range, (3) the Wasatch Range, and (4) the

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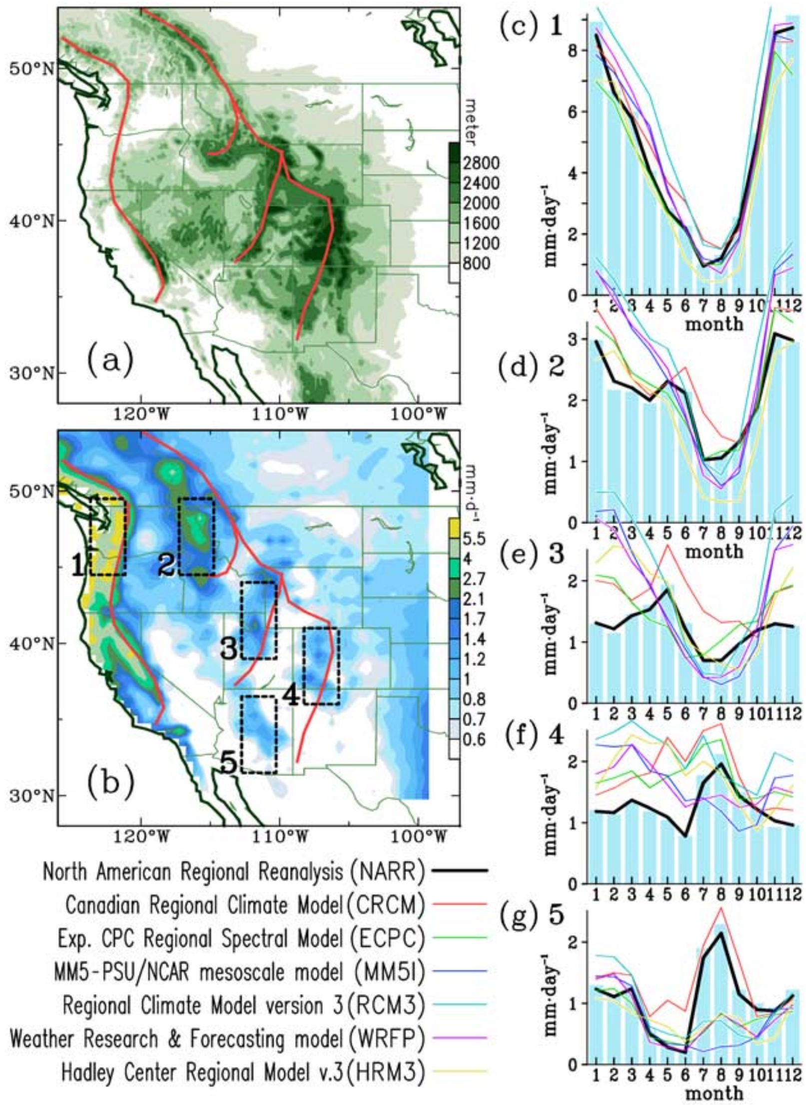


**Figure 1.** (a) Orography and (b) cold-season rainfall (November–May, UDel) of the Intermountain Region. The major mountain ranges are outlined by red lines. (c)–(g) Monthly rainfall histograms of UDel, averaged from the five regions indicated in Figure 1b, superimposed with the corresponding precipitation of the NARR (thick black line) and all RCMs (color lines). Note the precipitation scale in Figure 1c is twice of that in Figures 1d–1g. The abbreviations of the RCMs and their designated colors are given under Figure 1b.

Colorado Rockies, denoted as regions 1–4 (Figure 1b). Precipitation occurs mainly on the windward side of these mountain ranges during the cold season [*Leung et al.*, 2003a]. Monthly evolutions of the observed and simulated precipitation in regions 1–4 and central Arizona (region 5) were averaged over 3° long. × 6° lat. domains covering the maximum centers of precipitation across the region (Figure 1b). From regions 1 to 5 (Figures 1c–1g), the seasonal cycle evolves from a winter regime toward the summer regime with increasing semiannual variability. Spring precipitation becomes important in region 2 and peaks in region 3, but then decreases in regions 4 and 5 where a monsoon rainfall regime prevails in July and August [e.g., *Higgins et al.*, 1997]. The NARR precipitation (black line) is generally consistent with the UDel (histogram).

[6] In the Cascade Range (region 1) where the annual cycle is dominant, the phases of the RCM precipitation show marked consistency with the observations. Beginning at region 2, precipitation phases of the RCMs increasingly depart from the observations, and the precipitation amounts are consistently too large during winter. In region 3 where the annual cycle is weak, half of the RCMs are dominated by a strong annual cycle and do not capture the spring precipitation (Figure 1e). In region 4 where winter precipitation and summer monsoon are important factors, the RCM precipitation is largely inconsistent with that observed. The simulated monsoon precipitation in region 5 is not revealed, except by CRCM. Seasonal precipitation amounts of the RCMs and UDel can be viewed in the NARCCAP website at http://www.narccap.ucar.edu/results/ncep-results.html.

[7] Using Fourier analysis, the monthly precipitation was filtered into an annual cycle (wavenumber 1) and a semiannual cycle (wavenumber 2) and then subjected to PC analysis, obtaining two PCs for each cycle. In precipitation, PCs 1 and 2 of the annual cycle normally represent the winter-summer and spring-fall modes, respectively, while

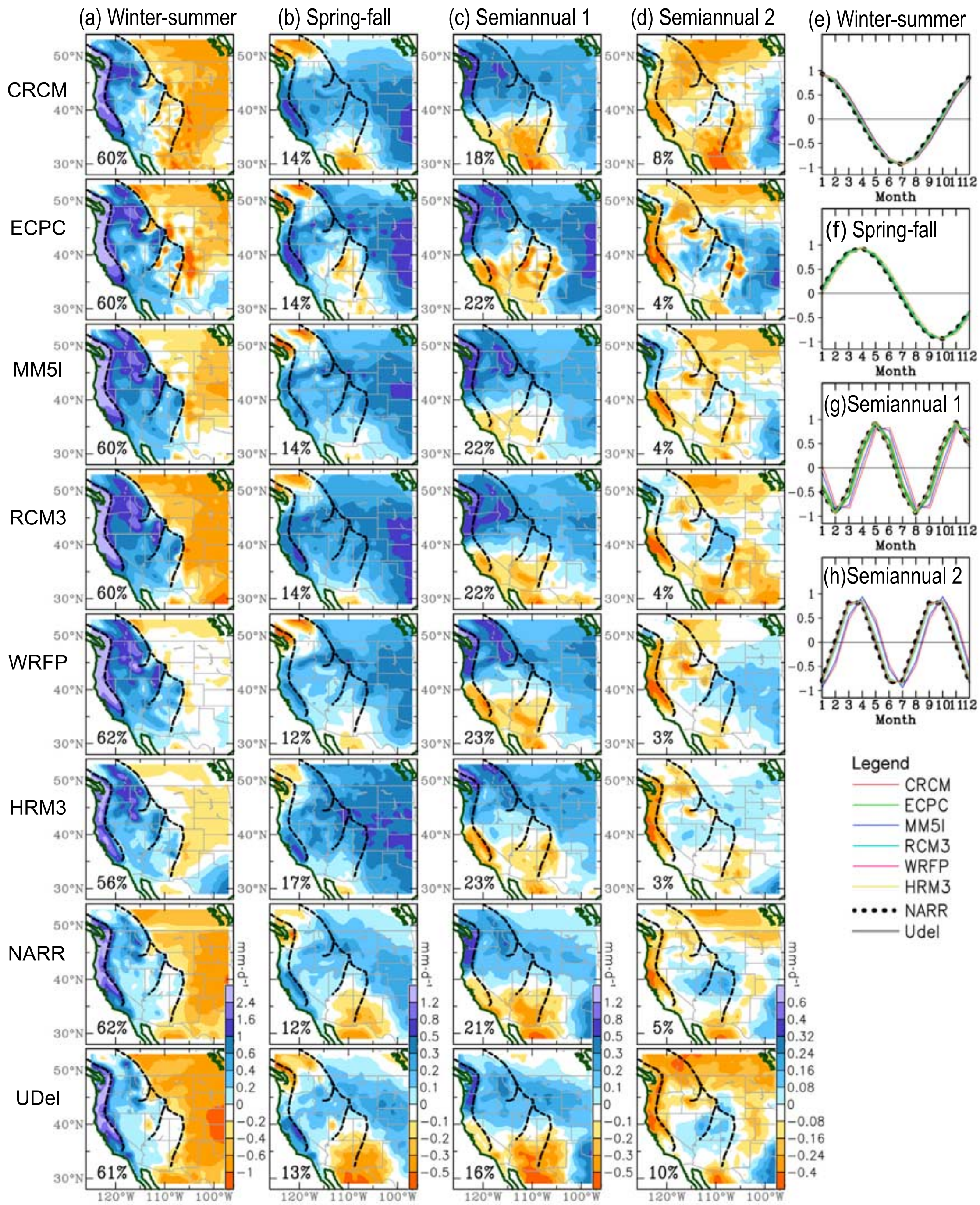


**Figure 2.** Eigenvectors of the annual and semiannual cycles representing the (a) winter–summer mode, (b) spring–fall mode, (c) first semiannual mode, and (d) second semiannual mode. The percentage of variance explained is given in the lower left of each panel. The data names are indicated to the left of Figure 2a. (e)–(h) Normalized eigencoefficients of each mode corresponding to Figures 2a–2d. The major mountain ranges are outlined by black dashed lines as in Figure 1a.

PCs 1 and 2 of the semiannual cycle depict the first and second semiannual modes [*Wang and Chen*, 2009]. Results are indicated in Figure 2. Each map in Figures 2a–2d is the eigenvector of the particular mode, while its corresponding normalized eigencoefficient is shown in Figures 2e–2h. The percentage of each mode (bottom-left in each panel) indicates the variance of the seasonal precipitation explained in terms of the combination of annual and semiannual cycles.

[8] A striking feature of the winter-summer mode (Figure 2a) is that the precipitation patterns are clearly divided by the Rocky Mountains, with local maxima on the windward sides. This feature reflects the seasonal march of upper-level flows interacting with the orography, with stronger westerlies in winter and weaker westerlies in summer. However, all models have a tendency to produce too much winter precipitation in regions 2–4, although the wet bias in CRCM is not as pronounced. Three of the models (MM5I, WRFP, and HRM3) produce a weak annual cycle of precipitation east of the Rockies. In the spring-fall mode (Figure 2b), the north–south seesaw pattern visible in

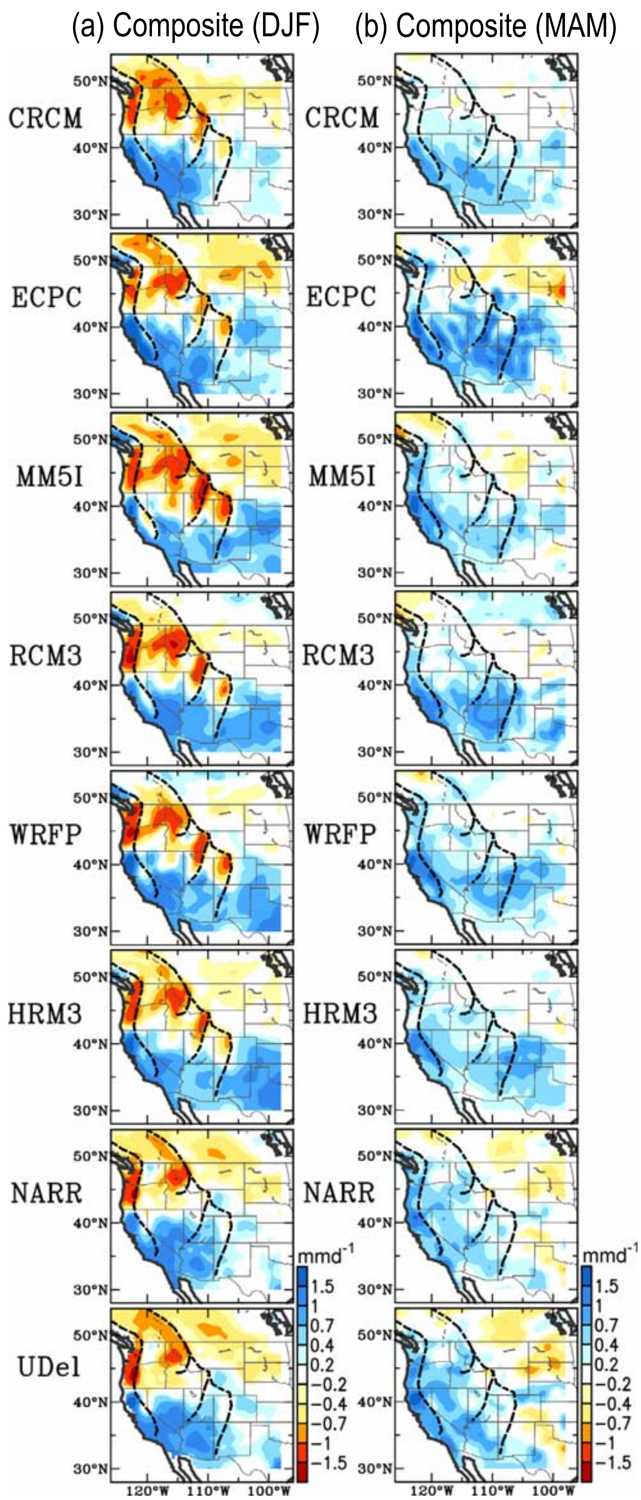


**Figure 3.** (a) Differences of precipitation composites between El Niño and La Niña winters (December–February). (b) Same as Figure 3a but for the subsequent springs (March–May). The major mountain ranges are outlined by black dashed lines as in Figure 1a. Contour intervals are given in the lower right.

the observations is not as clear in most of the RCMs, where the simulated spring precipitation tends to encompass much of the Southwest. In addition, the magnitudes of the spring-fall mode in all models are too large. Despite such differences, the RCMs do produce realistic phases for both annual modes (Figures 2e and 2f).

[9] In contrast to the documented deficiency of GCMs to simulate the semiannual cycle [e.g., *Boyle*, 1998], the RCMs do produce fairly consistent patterns in the first semiannual mode (Figure 2c). This mode features a distinct north–south seesaw pattern similar to that in the spring-fall mode and consistent with *Hsu and Wallace* [1976]. The mechanism forming the spring-fall and semiannual modes of precipitation in the IR is not well understood; however, both modes change phase in July (Figures 2f and 2g) and thereby suggest a link with the development of the North American Monsoon (NAM). For example, *Higgins et al.* [1997] showed that the NAM onset is accompanied with a change in the upper-level circulation regime that evolves from a large-scale trough into a quasi-stationary anticyclone over the IR. The circulation regime change is followed by a precipitation phase reversal in the north–south direction, similar to that shown in Figures 2b and 2c; i.e., in the observations. The second semiannual mode (Figure 2d), the smallest in the annual and semiannual cycles, delineates a precipitation center in regions 3 and 4 (observations). This mode is where the largest deviations between models and observations were found. For instance, CRCM simulates too much precipitation in the Southwest but too little in regions 3 and 4, while MM5I, WRFP and HRM3 appear to displace the precipitation center. In region 1, the phase of this semiannual mode is reversed in MM5I and RCM3, leading the precipitation to drop in December (Figure 1c). In addition, two of the six RCMs reveal a one-month phase lag in both semiannual modes (Figures 2g and 2h).

[10] Numerous studies [e.g., *Dettinger et al.*, 1998; *Gershunov and Barnett*, 1998; *Leung et al.*, 2003b] have pointed out that the western U.S. climate undergoes a pronounced modulation due to ENSO which develops a north–south precipitation pattern. However, as alluded to earlier, the central IR is shielded from direct influence of ENSO [*Rajagopalan and Lall*, 1998] as well as the Pacific Decadal Oscillation [*Wang et al.*, 2009a]. The interannual precipitation pattern associated with ENSO is revealed by differences (i.e., anomalies) of the composites between the El Niño (1982/83, 87/88, 91/92, 94/95, 97/98, 2002/03) and La Niña (1984/85, 88/89, 95/96, 98–2001) winters (Figure 3a), based on ENSO events identified by the Climate Prediction Center (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.ERSST.v3.shtml). Figure 3a confirms that the typical north–south precipitation pattern over the western U.S. is reasonably simulated by the RCMs and is consistent with the results presented by *Leung et al.* [2003b]. However, the RCM precipitation anomalies near regions 3 and 4 are consistently too large compared to the observations. The same composites between the RCMs and the observations made for the subsequent spring seasons (Figure 3b) do not reveal such a systematic bias.

[11] It is known that precipitation variations in the central IR are not exactly in-phase, but are "non-linearly" coupled, with ENSO. Precipitation variations in the 3–6 yr frequency [*Rajagopalan and Lall*, 1998] and the 10–15 yr frequency

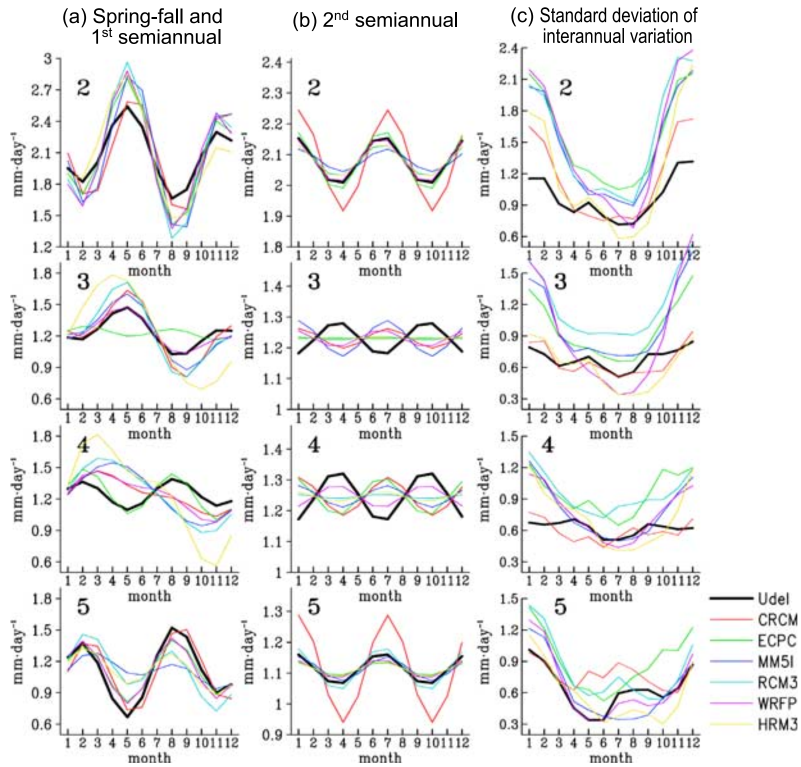


**Figure 4.** (a) Same as Figures 1d–1g but for precipitation reconstructed by the spring–fall mode and the first semiannual mode (see text). (b) Same as Figure 4b but reconstructed from the second semiannual mode with the y-scale enlarged. (c) Monthly standard deviations of interannual variability in each region.

[*Wang et al.*, 2009a, 2009b] were found to lag ENSO by a quarter-phase. This feature is identified by the weak precipitation anomalies near regions 3 and 4 in the observations (Figure 3a). In the RCMs, however, significant ENSO signals extend from the Pacific Northwest to the central IR. It appears that most RCMs simulate the ENSO impacts too far inland in response to the excess winter precipitation simulated in regions 3 and 4 (see Figure 2a). An intuitive explanation for this bias is that RCM fields are more strongly influenced by the R-2 boundary forcing near the coast than near the central IR. Investigation of this winter precipitation bias is currently underway.

## 3. Discussion

[12] The central IR (i.e., regions 2–4) is a transition zone of different climate regimes in both the seasonal and interannual time scales, so it is not surprising that RCM performances are weakest here. Most RCMs have a tendency to produce too strong an annual cycle, which obscures their relatively good performance in the primary (first) semiannual cycle. We confirmed this by reconstructing the precipitation seasonal cycle for regions 2–5 with only the spring-fall mode and the first semiannual mode (Figure 4a). This was done by multiplying the eigenvector of each mode with the eigencoefficient and then summing the desired modes. For comparative purposes, the reconstructed RCM precipitation anomalies were added to the annual mean of the UDel precipitation. Without the winter-summer mode, the precipitation phases of most RCMs agree well with that observed in regions 2, 3 and 5, regardless of the amplitude differences. In region 4, the model biases echo their overly strong spring-fall modes that are out-of-phase (Figure 2b). For the second semiannual mode (Figure 4b), the RCM precipitation is consistent with the observations in regions 2 and 5 but is mostly out-of-phase in regions 3 and 4, signaling the difficulty of the RCMs to handle the localized climate in the central IR.

[13] To verify if the winter wet bias is crucial to the bias in interannual variability, monthly standard deviations of year-to-year variations in regions 2–5 are shown in Figure 4c. Compared with the observations, the interannual variability of the RCM precipitation is consistently too large during winter. Some RCMs feature a year-long wet bias in all regions (e.g., ECPC and RCM3), while some (e.g., CRCM and HRM3) appear to perform better in the summer months. This enhances the possibility that the false ENSO signal found in the central IR is linked to the winter wet bias.

[14] The results presented here suggest that caution should be exercised in interpreting the RCM precipitation simulated for the IR, specifically the seasonal cycle and the interannual variability. Despite the observed model biases, the RCMs produce an overall realistic precipitation climatology in the IR. In contrast to the noted limitation of GCMs to reproduce the spring-fall and semiannual modes, the RCMs show a distinct improvement in generating accurate phases and amplitudes of the seasonal cycle. The winter-summer modes in all RCMs are precisely divided by the Rocky Mountains, indicating a well-handled terrain-flow interaction. The reasonably simulated ENSO influences in the western IR encourage use of RCM results for climate impact assessments.

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