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SIMULATED IMPACTS OF EL NIÑO/SOUTHERN OSCILLATION ON UNITED STATES WATER RESOURCES[1]

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ABSTRACT: The El Niño/Southern Oscillation (ENSO) phenomena alter global weather patterns with consequences for fresh water supply. ENSO events impact regions and their natural resource sectors around the globe. For example, in 1997 and 1998, a strong El Niño brought warm ocean temperatures, flooding, and record snowfall to the west coast of the United States. Research on ENSO events has improved long range climate predictions, affording the potential to reduce the damage and economic cost of these weather patterns. Here, using the Hydrologic Unit Model for the United States (HUMUS), we simulate the impacts of four types of ENSO states (Neutral, El Niño, La Niña, and strong El Niño) on water resources in the conterminous United States. The simulations show that La Niña conditions increase water yield across much of the country. We find that water yield increases during El Niño years across the south while declining in much of the rest of the country. However, under strong El Niño conditions, regional water yields are much higher than Neutral, especially along the West Coast. Strong El Niño is not simply an amplification of El Niño; it leads to strikingly different patterns of water resource response.

(KEY TERMS: modeling; ENSO; climate; water resources impacts.)

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INTRODUCTION

The El Niño of 1997 and 1998 was felt strongly along the west coast of the United States (U.S.). Exotic tropical fish species traveled north with the warmer Pacific waters, and strong storms with record rain and snowfall caused landslides on the west coast and impacted agriculture, recreation, water supplies and electricity generation (New York Times, 1997, 1998; Gaura, 1998; Giesin, 1998; Martin, 1998). That El Niño event prompted a great deal of research into the causes, severity, and impacts of the El Niño/Southern Oscillation (ENSO) phenomena.

ENSO events originate in a sea surface temperature (SST) anomaly in the eastern tropical Pacific Ocean. A shift in the atmospheric sea level pressure gradient between Darwin, Australia, and Tahiti, French Polynesia, is associated with these SST anomalies – a warm SST anomaly leads to an El Niño event while a cold anomaly results in a La Niña (sometimes referred to as El Viejo) event. Although they differ greatly in strength, timing, and duration, El Niño and La Niña occur every two to nine years, and usually last for one to two years. Global average temperatures are anomalously warm during El Niño years, although specific regional impacts vary widely. In general, La Niña results in climate patterns that are different and sometimes of opposite sign from those of El Niño. Over the U.S., El Niño events cause the jet stream to shift southward resulting in warmer temperatures, with the exception of cooler temperatures in the Southwest, and variable regional changes in precipitation (Leung *et al.*, 1999; Green *et al.*, 1997). These anomalies in turn affect water resource availability through changes in precipitation amount, timing, and intensity, as well as impacts on vegetation growth and evaporative demand.

Streamflow anomalies worldwide have been associated with ENSO events. In Australia, Chiew *et al.* (1998) found that reduced precipitation and stream-

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flow were linked to El Niño conditions and that information on past impacts could be used to effect statistically significant improvements in streamflow forecasts. Wooldridge *et al.* (2001) found that ENSO caused a strong but nonlinear response of runoff to precipitation anomalies in Australia. They attribute the nonlinearities to other climatic factors influenced by ENSO, such as rainfall intensity and duration, air temperature controls on evaporation, and soil and land cover characteristics.

ENSO events significantly affect streamflow in the U.S. (Kahya and Dracup, 1993; Dracup and Kahya, 1994) especially along the Gulf Coast, the Northeast, and the Pacific Northwest. In a study of drought conditions in the U.S., Piechota and Dracup (1996) found that El Niño events generally cause droughts in the Pacific Northwest while La Niña brings drought to much of the southern U.S. ENSO events strongly impact the Pacific Northwest. Consequences for water supply in that region were examined in detail by Leung *et al.* (1999) using regional climate and hydrology models. They found that the higher temperatures associated with El Niño increased the proportion of precipitation that falls as rain, consequently reducing the spring snowmelt. This, in combination with reduced winter precipitation, reduces streamflow in the Columbia River basin. Clark *et al.* (2001) examined the effects of ENSO events on snowpacks in the Columbia and Colorado River basins. They found a significant decline in snowpack in the Northwest under El Niño conditions and an increase under La Niña conditions; anomalies were of opposite sign in the Colorado basin. They concluded that information on ENSO events and their impacts on monthly precipitation can be used to improve the accuracy of runoff predictions.

Evidence from the strong Los Niños of 1997 and 1998 and 1982 and 1983 indicates that regional temperature and precipitation anomalies associated with the highest SST anomalies differ not only in magnitude but also in sign from weaker Los Niños. An analysis of the 1997 and 1998 event by the National Weather Service noted that the strong Los Niños of 1997 and 1998 and 1982 and 1983 produced different atmospheric circulation anomalies than did the weaker Los Niños of 1986 and 1987 and 1991 and 1992. This resulted in unexpected impacts; instead of an expected wet spring in the south and southeast, the region experienced a severe drought as a dome of high pressure moved farther north from Mexico than expected, blocking storm systems (Barnston *et al.*, 1999). A separate study of the 1997 and 1998 El Niño found that temperature and precipitation anomalies were a significant amplification of normal El Niño conditions, and that some temperature and precipitation patterns were the opposite in sign of those predicted. In the Pacific Northwest, a wetter than normal spring was expected, but drier than normal conditions occurred due to the changed patterns with the strong El Niño (Smith *et al.*, 1999). In the study reported here we simulate the impacts of ENSO events on water resources across the 48 conterminous U.S., distinguishing between El Niño, strong El Niño, and La Niña conditions.

MATERIALS AND METHODS

Using 30 years of historical climate data from a single station in each of the 2,101 “eight-digit” basins defined by the U.S. Geological Survey (USGS), we calculate monthly mean temperature and precipitation deviations from the Neutral condition for El Niño, strong El Niño, and La Niña years. With these mean monthly values we generate a daily weather sequence and use it to drive the Hydrologic Unit Model of the United States (HUMUS) and the Soil Water Assessment Tool (SWAT) hydrologic models (Srinivasan *et al.*, 1993). By using these averaged weather records, we can examine ENSO events, their impact on water yield in distinct hydrological units, and the aggregate regional response.

ENSO Climate Scenarios

We developed scenarios for four different states of ENSO for this study based on a five-month running mean of spatially averaged SST anomalies over the equatorial eastern Pacific (Meyers *et al.*, 1999). The Japan Meteorological Agency (JMA) ENSO Index (i) defines El Niño years as six consecutive months (starting in October) of i greater than 0.5˚C. A classification of strong El Niño is given to years when i was greater than 2.0˚C for two or more consecutive months between October and March. La Niña is defined similarly, where i is less than -0.5˚C for six consecutive months (starting in October). Neutral is defined as the index being between plus or minus 0.5˚C. The “year” in the context of this work is defined as the October preceding the fall and winter period that defines the categorization through the following September. Of the period from 1960 to 1989, six years were classified as El Niño (1963, 1965, 1969, 1976, 1986, and 1987); seven as La Niña (1964, 1967, 1970, 1971, 1973, 1975, and 1988); and two as strong El Niño (1972 and 1982). The remaining 15 years were classified as Neutral.

Based on historical daily climate records, monthly climate statistics were calculated for each month of each ENSO year. These included means and distribution characteristics of temperature and precipitation. The stochastic weather generator (WXGEN) (Richardson and Nicks, 1990) used these monthly statistics for each ENSO state to simulate 30 years of daily weather at a site in each of the 2,101 basins under the average climatic characteristics of a given ENSO scenario. These ENSO scenarios (El Niño, strong El Niño, La Niña, and Neutral) provided a clear picture of the average weather anomalies associated with each ENSO state. These generated climates were used to drive the HUMUS water resources model. It should be noted that the use of average climate for each ENSO state applied over a continuous 30-year cycle ignores the effects of changes in ENSO state, for example from El Niño to a La Niña or Neutral year. This may cause some amplification of the water yield results since, for example, a wet year following a wet year would likely result in higher water yield than a wet year following a dry year.

Description of HUMUS/SWAT

HUMUS (Arnold *et al*, 1999; Srinivasan *et al.*, 1993) is a GIS based modeling system that provides input to drive SWAT (Arnold *et al.*, 1994, 1998). For the study reported here, HUMUS was run at the subbasin level of 2,101 USGS defined eight-digit hydrologic unit areas (HUAs). The dominant soil type, land use, and vegetation in each eight-digit HUA are used to describe the entire modeling unit. Climate records for each basin are drawn from a single weather station – that nearest the geographic centroid of the basin.

SWAT represents the water balance in each basin through four storage volumes; snow, soil profile, shallow aquifer (2-20 m), and deep aquifer (> 20 m). SWAT simulates important hydrologic and related biophysical processes including infiltration, evapotranspiration (ET), net primary productivity, lateral flow, and percolation. Surface runoff is estimated using a modification of the Soil Conservation Service curve number method (USDA, 1972). SWAT runs on a daily time step using the weather variables of maximum and minimum temperature, precipitation, humidity, radiation, and windspeed. The output variable that most closely represents streamflow is water yield – the sum of surface and lateral flows from the soil profile plus ground water flow from the shallow aquifer. For this simulation, we assume natural streamflow, which differs from actual (observed) streamflow because it assumes no anthropogenic influences such as large scale storage in dams or diversions and withdrawals for industrial, municipal, or agricultural use. While SWAT is capable of simulating the impacts of impoundments and diversions on streamflow, the number and complexity of these across the nation prohibits their inclusion in this continental scale study.

Model Validation

Previous validations have shown that HUMUS accurately simulates natural streamflow throughout the U.S. at the eight-digit basin scale. SWAT simulated streamflow has been validated against observed hydrologic data for areas ranging in size from a small watershed (Arnold and Allen, 1996) to a major water resource region (Arnold *et al.*, 2000). In the latter work, SWAT simulated estimates of base flow and recharge were calibrated with observed streamflow at a gauging station in Alton, Illinois, in the Upper Mississippi basin. After model calibration SWAT monthly streamflow explained 65 percent of the variance of observed monthly data there for the years 1981 through 1985. Gerbert *et al.* (1987) estimated annual natural streamflow from observations at 5,951 U.S. gauging stations from 1951 through 1980 and these data (hereafter USGS estimated) have been used in several studies. In a recent study, Brown *et al.* (2000) compared HUMUS simulated streamflow from the 1960 through 1989 weather record to USGS estimated historical streamflow from 1951 through 1980 in the 18 major water resource regions (MWRRs) of the conterminous U.S. reported by Wolock and McCabe (1999). Although reasonable agreement was noted, HUMUS tended to overestimate water yield in irrigated basins and underestimate it in mountainous regions. Arnold *et al.* (1999) summarize previous validations of SWAT for a range of hydrologic variables and locations.

We compare the USGS estimated natural streamflow values from Gerbert *et al.* (1987) with HUMUS simulated natural streamflows at the MWRR scale and at the modeling scale of eight-digit basins. We note that the periods of record in this comparison are not identical. Our simulations are based on a weather record from 1960 through 1989 and Gerbert *et al.* estimates are from 1951 through 1980. Records of actual streamflow do exist for the 1960 through 1989 time period, but the available estimates of natural streamflow are inadequate for our validation needs. The simulated baseline water yields agree well with the USGS estimated values when aggregated to the MWRR scale ($R^2 = 0.96$). There is greater variation at the eight-digit basin scale, but agreement between simulated and observed streamflow is statistically significant within all but one of the 18 MWRRs (Table 1). Agreement is poor in the Lower Mississippi basin, likely due to a combination of HUMUS overestimation in agricultural regions and a large proportion of the streamflow in this region originating upstream (Upper Mississippi). In general, HUMUS underestimates streamflow at the MWRR level.

RESULTS

Seasonal and Geographic Patterns of ENSO Climate Impacts

The ENSO climate scenarios had a range of impacts on temperature and precipitation at individual stations, some of which were quite significant. Here we summarize the general climate anomalies, noting that the regional impacts are generally not as large as those realized at individual stations and that significant variance can be realized at stations within each MWRR.

Temperature

Temperature changes are small in winter under El Niño conditions, and do not show a consistently strong pattern over the year (Table 2a). Persistent warming occurs in some Eastern and Midwest basins, including the Lower Mississippi, and in California in spring and summer, but like the Pacific Northwest most regions experience modest temperature change. Under La Niña, temperatures increase across most regions in the winter but show little change over the remainder of the year. Winter temperatures increase substantially from Neutral in strong El Niño years throughout the eastern part of the country, while some western regions experience cooler temperatures (Table 2a). The cooler temperatures in the west continue into spring while the eastern regions experience normal to cool temperatures. A slight warming returns in summer to the western regions and is replaced by cooler than normal temperatures in the fall.

TABLE 1. Comparison of HUMUS Simulated Water Yield With USGS-Estimated Streamflow (mm) (Gerbert *et al.*, 1987) Using Mean Annual Values for Each Eight-Digit Basin in the 18 Major Water Resource Regions.

HUA 2	**Region**	**No. of Observations**	**Observed Mean[a]**	**Simulated Mean[b]**	**RMSE**	**R^2**	**Slope**	**y-Intercept**
01	New England	51	630	497	146	0.46	0.53	365
02	Mid-Atlantic	90	490	376	127	0.61	0.85	167
03	South Atlantic-Gulf	194	423	381	96	0.69	0.92	82
04	Great Lakes	107	343	228	121	0.60	0.96	98
05	Ohio	119	448	360	108	0.66	0.97	95
06	Tennessee	31	642	525	162	0.51	0.77	243
07	Upper Mississippi	129	205	177	44	0.72	1.02	25
08	Lower Mississippi	81	479	422	160	0.05[c]	0.10	438
09	Souris-Red-Rainy	41	69	62	30	0.83	0.95	8
10	Missouri	306	76	52	89	0.40	1.04	22
11	Arkansas-White-Red	172	139	124	45	0.94	1.16	-7
12	Texas Gulf	121	98	102	43	0.86	1.06	-7
13	Rio Grande	68	22	10	34	0.55	1.35	3
14	Upper Colorado	60	93	36	105	0.46	1.40	46
15	Lower Colorado	83	16	17	19	0.53	0.98	0
16	Great Basin	70	36	25	82	0.69	2.09	-11
17	Pacific Northwest	216	484	264	390	0.87	1.33	152
18	California	130	236	204	189	0.72	1.08	14

[a] Mean value of USGS estimated natural streamflow using values by eight-digit HUA.
[b] Mean value of HUMUS simulated water yield using average annual values by eight-digit HUA.
[c] Regression not significant at p-value > 0.0001.

TABLE 2a. Seasonal Average Temperature (˚C) at Neutral and Deviation From Neutral for the 18 Major Water Resource Regions (EN = El Niño; LN = La Niña; SEN = Strong El Niño).

	Fall				**Winter**				**Spring**				**Summer**			
	Neutral	**EN**	**LN**	**SEN**	**Neutral**	**EN**	**LN**	**SEN**	**Neutral**	**EN**	**LN**	**SEN**	**Neutral**	**EN**	**LN**	**SEN**
MWRR	**T (˚C)**	**Change in T**			**T (˚C)**	**Change in T**			**T (˚C)**	**Change in T**			**T (˚C)**	**Change in T**		
01	8.7				-6.2			+	5.7			+	18.7			+
02	12.0				-1.6		+	++	9.8				21.4			+
03	18.6				8.5	-	+	+	17.7			-	26.0			
04	9.1				-6.5		+	++	6.2	+			19.1	+		+
05	12.7				-1.1		+	++	11.1	+			22.2	+		+
06	14.5				2.7	-	+	+	13.6			-	23.2		-	
07	10.0				-7.4		+	++	8.3	+			21.3	+		+
08	18.1				6.6		+	+	17.5			-	26.5			
09	5.8			-	-13.9	+		++	4.2	+		+	18.7	+		+
10	9.1			-	-5.6	+	+	+	7.8			-	20.8			
11	15.3			-	2.4		+		14.2			-	25.4		-	
12	19.9			-	9.0		+		19.4			-	27.8		-	-
13	14.5				4.6		+		14.3		+	-	23.6			
14	8.4			-	-4.1			-	6.9			-	19.1			
15	16.6			-	6.7	-	-	-	14.5			-	25.9		-	-
16	9.2			-	-1.5			-	7.5			-	19.6			
17	8.7				-0.5				7.6				17.6			
18	14.6	+			7.2				12.0	+	+		20.8			

Notes: -0.5 < T < 0.5 = No change.
-2 < T < -0.5 = -.
0.5 < T < 2 = +.
T > 2 = ++.

Precipitation

Precipitation is reduced in most regions and seasons under El Niño conditions (Table 2b). Winter is the season of greatest precipitation change with lesser declines persisting through the entire year. These declines are apparent in the western coastal regions as well as in the Lower Mississippi. In California, the largest decline in precipitation occurs in spring. Precipitation changes are more variable in La Niña years, increasing in the east and declining in the west in winter, spring and fall and reversing that pattern in the summer. As with temperature, the most persistent changes in precipitation occur during strong El Niño years, increasing significantly over much of the country during winter and spring. The Pacific Northwest is an exception; precipitation response to strong El Niño is relatively weak and variable, declining in spring and fall while increasing in winter and summer. Some eastern regions experience a slight drying in summer, but the wetter than normal conditions in the west persist year round.

ENSO Impacts on Simulated Seasonal Water Yield

El Niño. In most of the 18 MWRRs and in most seasons, water yield declines during El Niño years (Table 3). In percentage terms the negative anomalies are greatest in the Upper Colorado, Great Basin, and California in winter. Regions experiencing overall percentage increases in water yield include the South Atlantic, Texas, Gulf, and Rio Grande basins.

With El Niño conditions, water yields decline substantially in winter (-40 to -70 mm) in the Pacific Northwest and in Northern California and the Ohio Valley (Figure 1). In the northeast water yields also decline slightly. Water yields increase in winter in the south, notably in east Texas and Florida. Greater than normal water yield persists through the spring when increases also occur in the North Central Plains. The dryness in California and north along the West Coast persists. A notable drying occurs in spring in the mountainous areas of Idaho, where winter water yields are also lower than normal. Dryness also persists through the Ohio Valley and extends to states to the north and west. Dry conditions persist in the

TABLE 2b. Seasonal Average Precipitation at Neutral and Percentage Change From Neutral for the 18 Major Water Resource Regions (EN = El Niño; LN = La Niña; SEN = Strong El Niño).

	Fall				Winter				Spring				Summer			
	Neutral	EN	LN	SEN	Neutral	EN	LN	SEN	Neutral	EN	LN	SEN	Neutral	EN	LN	SEN
MWRR	P (mm)	% Change in P			P (mm)	% Change in P			P (mm)	% Change in P			P (mm)	% Change in P		
01	291		-	-	239	-		+	246	-		++	287	-		
02	260			+	213	-			255	-		++	307	--		-
03	272	+		+	311	+		++	321			++	404			-
04	232				141	--	+		191		+	++	265	-	-	-
05	256	-	+	-	222	-	+		303	-		++	321	-		-
06	301		+		326	-	+	+	371	-		++	327	-		-
07	216	-		+	100	--		++	221			++	317	-	-	-
08	321			++	328	+	+	++	390	-	-	++	324			-
09	121	-		++	48	-		--	126	+		--	232			+
10	112	-		++	48	--		+	159		-	+	199	-	-	--
11	204			+	104	+		++	231	-	-	++	239	-		--
12	245		-	+	132	++		++	203				209	-	+	++
13	122	-	--	-	44	+	-	++	58		--		141			--
14	93	-	--	+	68	--	-		78	--	--	+	78		-	++
15	89		--	++	86	--	--	++	53	-	--	++	96	+	-	
16	76	--	-	++	73	---	-		81	-	--	+	56		+	++
17	188	--		--	244	--	+	+	164	-		-	81		+	+
18	137	--	+	++	290	---	--	++	149	---	--	++	21	+	+	++

Notes: -0.5% < T < 0.5% = No change.
-20% < P < -5% = -.
-50% < P < -20% = --.
P < -50% = ---.
5% < P < 20% = +.
20% < P < 50% = ++.

Ohio Valley through the summer and fall and extend to the East Coast during summer. Wetter than normal conditions persist in Texas and Florida. Along the West Coast, water yields improve in summer but remain below normal. In fall the reductions in yield intensify in this region.

Strong El Niño. Patterns of the percentage change in water yield differ markedly under strong El Niño and El Niño. Under strong El Niño water yields increase in all MWRRs and seasons with the exception of the Pacific Northwest in the fall (Table 3). Generally the percentage of these increases are substantially greater under strong El Niño than in either El Niño or La Niña events.

Along the West Coast, where negative anomalies prevail in all seasons under El Niño, water yield under strong El Niño is above normal in winter, spring and summer, but drying occurs along the northern coast in fall (Figure 2). Another striking anomaly is the dramatic increase in water yield in the Mississippi Valley, strongest in winter and spring but evident throughout the year. This positive anomaly extends to the Southeast and north to the East Coast in spring and, to a lesser extent, in fall. Wetter than normal conditions persist year round in the Southwest and are strongest in spring. One similarity with El Niño is the appearance of lower than normal water yields in the mountains of Idaho, especially during spring. Overall, the geographic distribution, strength, and sign of water yield anomalies under strong El Niño conditions differ greatly from those under El Niño.

La Niña. With some exceptions La Niña conditions are correlated to a general increase, in percentage terms, in water yield across the country. Percentage changes in winter are smaller and, in many MWRRs, opposite in sign from those of El Niño (Table 3). This holds true through the spring and summer with a major exception in the western regions where water yields decline throughout the year.

Water yields increase most in winter in the Pacific Northwest and in the Lower and Eastern Mississippi Valley (Figure 3). Water yield quantities are reduced significantly in California and along the Gulf Coast.

TABLE 3. Water Yield Under Neutral Climate and the Percentage Change From Neutral for EN (El Niño), SEN (strong El Niño), and LN (La Niña) Climates for the Major Water Resource Regions of the U.S.

	Fall (SON)				**Winter (DJF)**				**Spring (MAM)**				**Summer (JJA)**			
	Neutral	**EN**	**SEN**	**LN**	**Neutral**	**EN**	**SEN**	**LN**	**Neutral**	**EN**	**SEN**	**LN**	**Neutral**	**EN**	**SEN**	**LN**
Region	**(mm)**	**% Change**			**(mm)**	**% Change**			**(mm)**	**% Change**			**(mm)**	**% Change**		
New England	122	-4	20	-10	104	-12	42	7	228	-7	31	1	95	-15	41	0
Mid-Atlantic	103	-1	27	1	126	-11	25	2	138	-9	31	1	103	-26	21	7
South Atlantic-Gulf	108	8	28	4	141	7	36	-2	153	4	45	-3	117	0	25	3
Great Lakes	62	-17	23	-5	52	-20	38	11	116	-20	20	8	64	-24	25	-4
Ohio	89	-30	13	8	133	-28	21	12	148	-16	27	1	106	-30	30	-2
Tennessee	140	-7	5	12	200	-9	25	14	205	-13	32	3	146	-16	9	9
Upper Mississippi	54	-43	48	-1	46	-46	62	8	94	-33	45	-3	73	-59	37	-22
Lower Mississippi	98	-2	49	9	149	6	59	16	154	-5	54	-5	86	-4	41	7
Souris-Red-Rainy	9	2	75	9	8	1	64	5	29	-3	12	6	10	-2	66	6
Missouri	14	-26	66	-13	9	-47	73	1	26	-15	61	-27	18	-26	59	-28
Arkansas-White-Red	36	-11	54	14	35	3	62	8	54	-5	56	-8	32	-20	56	8
Texas Gulf	30	6	60	10	28	26	60	8	39	18	55	13	23	5	69	15
Rio Grande	3	13	38	-19	4	8	51	-35	5	-10	54	-49	2	12	56	-24
Upper Colorado	8	-53	60	-71	12	-119	43	-39	24	-85	47	-50	7	-83	61	-52
Lower Colorado	6	-12	77	-180	9	-20	71	-134	10	-35	77	-190	6	-27	74	-135
Great Basin	5	-106	63	-45	12	-210	43	-36	19	-153	49	-77	5	-154	62	-40
Pacific Northwest	74	-51	-14	11	113	-30	17	19	131	-28	5	14	51	-24	18	11
California	51	-89	36	-9	97	-69	38	-24	101	-99	42	-30	47	-76	38	-32

These general patterns persist in the spring, although the wet anomaly in the Lower Mississippi Valley disappears. Water yields decline in spring in the Missouri region. Missouri, Iowa, and California also remain drier than normal through the summer and fall. The dryness along the Gulf Coast persists throughout the year. Positive water yield anomalies occur in the Southeast and Ohio Valley through the summer and fall, while the strong positive anomalies along the Pacific coast diminish somewhat.

DISCUSSION AND CONCLUSIONS

Water yield, as simulated by HUMUS, is sensitive to the climate impacts of ENSO events. Under El Niño and La Niña conditions the Pacific Northwest, California, the Southeast, and the Corn Belt regions experience the greatest impacts. These regions, as well as the Mississippi Valley, the Northeast, and the Gulf and Southeast Coasts are also strongly affected under strong El Niño. In general, changes in water yield follow changes in precipitation for each ENSO state. The main exception in this study occurs under El Niño conditions in the Pacific Northwest and California in the spring and summer when vegetative use of water is high due to higher than normal temperatures; therefore greater than normal precipitation results in lower than normal water yield.

Increased water yields are simulated in the South and Southeast under El Niño, and are amplified under the strong El Niño scenario. These increases are likely due to the strong, southerly shift of the jet stream and consequent transport of moisture from the Gulf of Mexico to the Southern U.S. In the Ohio and Upper Mississippi Valleys, water yield is lower than normal under El Niño conditions, influenced by an enhanced atmospheric ridge over Southern Canada that has been observed in El Niño years (Barnston *et al.*, 1999).

Consistent with the findings of Leung *et al.* (1999) and Clark *et al.* (2001) we find that winter temperature increases in the Pacific Northwest result in a smaller snowpack and consequently greater winter runoff and lower than normal spring runoff, an effect most apparent under El Niño conditions because of water yield declines. Barnston *et al.* (1999) found that this mild pattern results from a stronger and more persistent low pressure center in the Gulf of Alaska and upper level ridge over the northwest coast of North America. Under La Niña conditions, a high

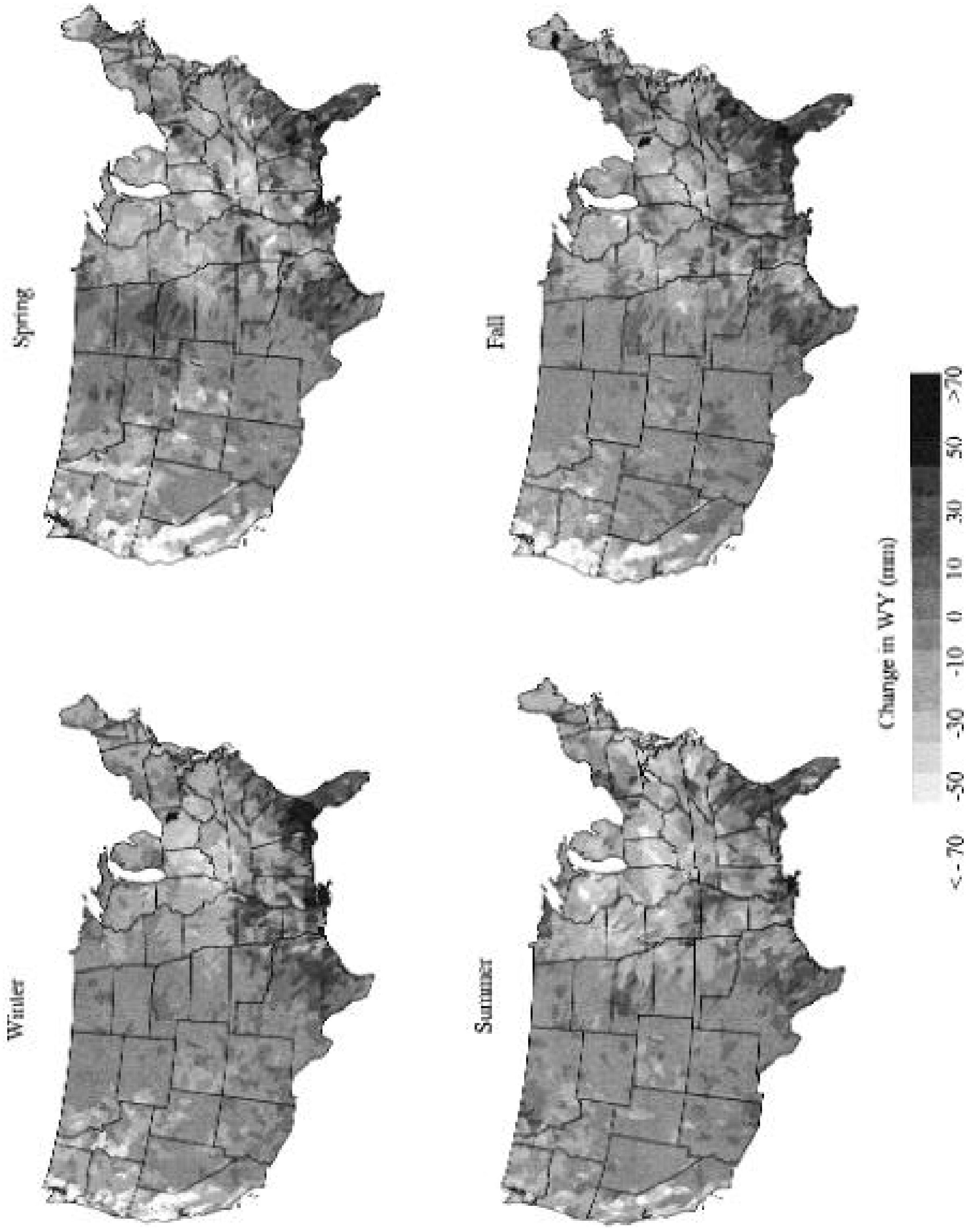

Figure 1. Water Yield (WY) Change From Neutral for El Niño Conditions by Season.

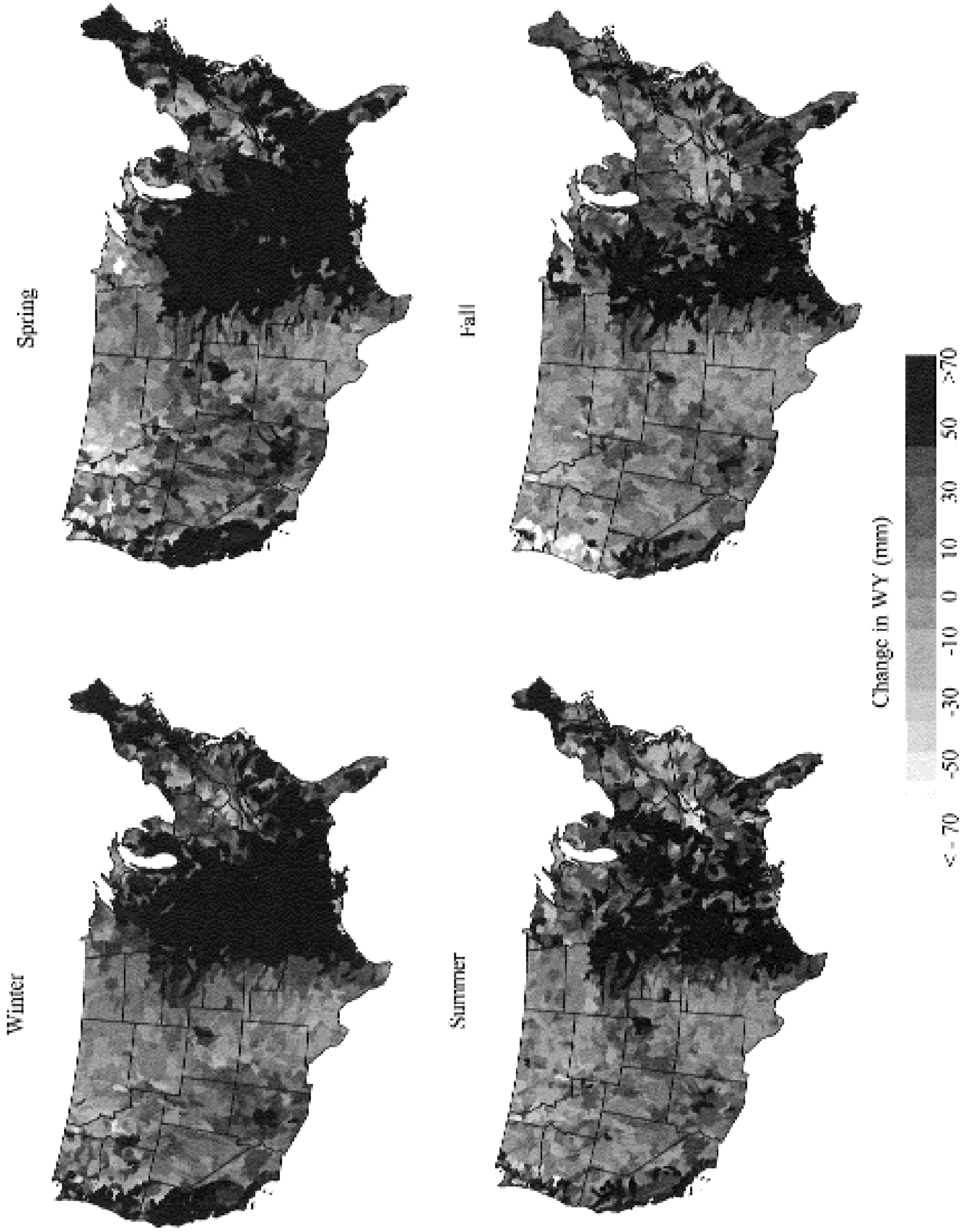

Figure 2. Water Yield (WY) Change From Neutral for Strong El Niño Conditions by Season.

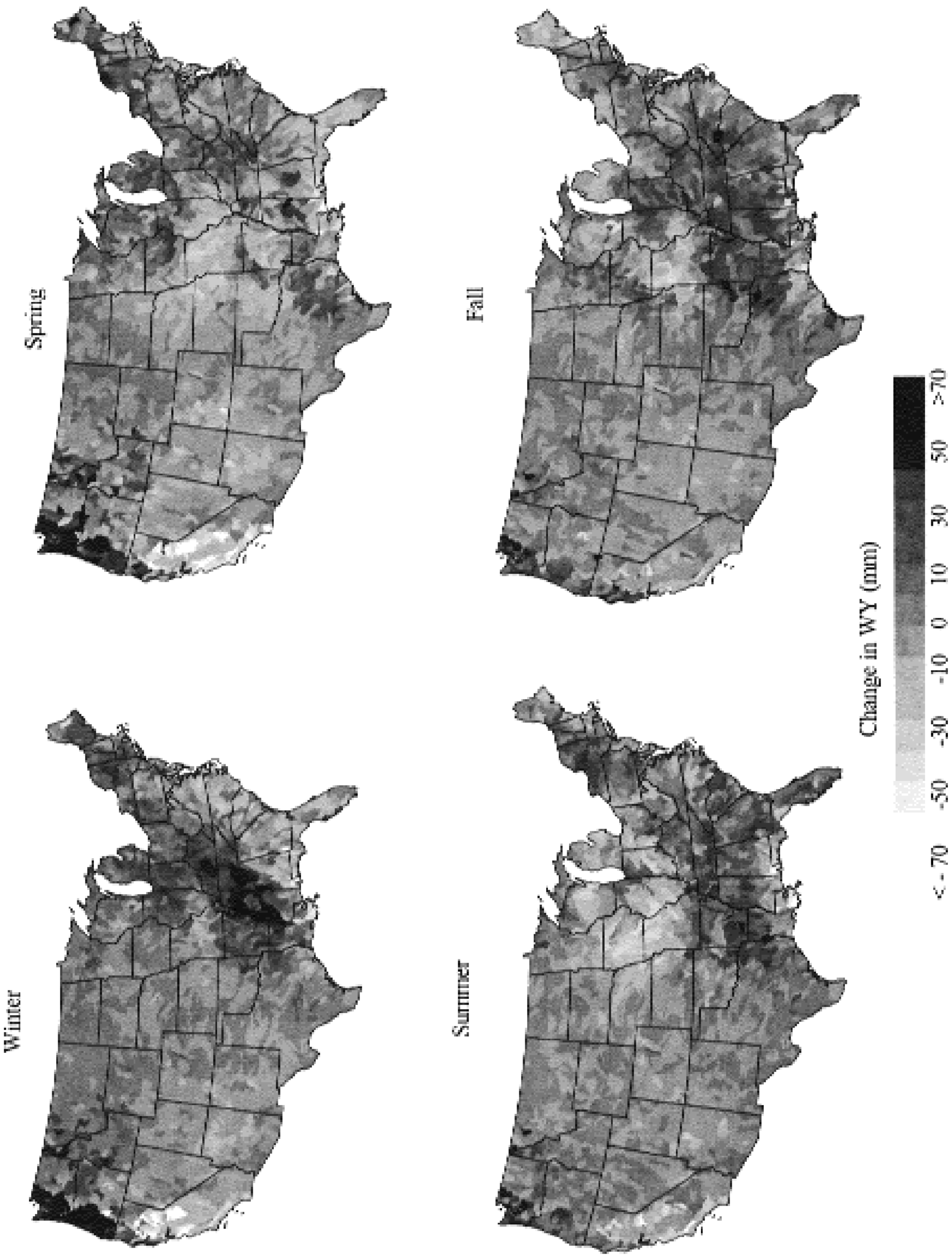

Figure 3. Water Yield (WY) Change From Neutral for La Niña Conditions by Season.

pressure center persists in this region and the Pacific Northwest experiences wetter than normal conditions, leading to higher than normal water yields (NOAA, 2002).

The impacts of the strong El Niño events are different, in kind as well as degree, than those that occur under El Niño. In California, dry under El Niño, water yields increase substantially under strong El Niño. Also, in the Ohio Valley and Corn Belt regions that experience drying under El Niño, water yields increase quite substantially under strong El Niño. These findings are supported by studies of the strong El Niño of 1997 and 1998 (JMA ENSO Index > 2.0˚C) (Smith *et al.*, 1999), where the weather anomalies recorded are reproduced here with the strong El Niño scenario. These recent observations provide additional evidence that Los Niños of differing strength can produce impacts on water resources and agriculture that differ not only in quantity but also in sign (Izaurralde *et al.*, 1999) and that the distinction we make between El Niño and strong El Niño could prove useful for improving the accuracy of long term forecasts. Differences in water yield of the sort simulated in this study are significant enough to require that water managers take them into account in preparedness planning. With confidence in the reliability of long-range forecasts of drought or flood conditions, water managers and the stakeholders who rely on their decisions can take steps to minimize economic damage and optimize benefits of ENSO events.

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