

Associations between Grain Crop Yields in Central-eastern Argentina and El Niño-Southern Oscillation

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Submitted to *Journal of Climate*

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Abstract. Associations are investigated between yields of major crops in the Argentine Pampas (central-eastern Argentina) and El Niño-Southern Oscillation (ENSO) phase. Maize and sorghum show a tendency towards higher (lower) yield anomalies during warm (cold) ENSO events. In both cases, the depression of yields during cold events is, on average, larger and less variable than yield increases during warm events. A yield decrease during cold events is also observed in soybean yields, although the effect of warm events is not significant. Cold events appear to be slightly more favorable for sunflower yields. Wheat, the only winter crop considered, did not show an association with ENSO. Precipitation anomalies during late spring-summer (the period with strongest ENSO signal in the Pampas) are summarized through principal component analysis. Precipitation anomalies during November-January are significantly correlated with maize, sorghum, and soybean yield anomalies. In turn, those precipitation anomalies show a distinct ENSO signal. Late spring-early summer precipitation, then, appears to mediate associations between ENSO phase and yields of maize, sorghum, and soybean in the Pampas.

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1. Introduction

Agriculture is one of the human activities most affected by climate and weather variability. The El Niño-Southern Oscillation (ENSO) phenomenon, the result of a two-way interaction between the ocean and the atmosphere in the tropical Pacific Ocean, is the major single source of climate variability on seasonal-to-interannual scales in many parts of the world (Trenberth 1996; Trenberth 1997a). The ENSO phenomenon involves two extreme phases: warm events, known as El Niño years, and cold events, referred to as La Niña or El Viejo years; years which do not fall in the extreme phases are labeled as “Neutral”.

Recent advances in our understanding of air-sea interactions and in observational systems have made it possible to forecast with usable skill the occurrence of ENSO events with lead times of several months (Barnston et al. 1994; Chen et al 1995). It is assumed that the routine availability of ENSO-related climate forecasts will benefit the agricultural sector by allowing farmers to mitigate potential negative consequences of climate variability or, alternatively, capitalize on potentially beneficial effects (Adams et al. 1995; Mjelde et al. 1997). However, a necessary initial step in assessing the usefulness of climate forecasts for agriculture in a region is to characterize the vulnerability of this sector to ENSO-related climate variability.

The goal of this work is to explore associations between grain crop yields and ENSO-related climate variability in the region of central-eastern Argentina known as the Pampas (Figure 1). The Pampas are one of the major agricultural regions in the world; a large proportion of Argentina’s crop production originates in this region. Hall et al. (1992) provide a thorough description of the climate, soils, and crop production systems in the Pampas.

ENSO events influence precipitation and temperature regimes in southeastern South America, including the Pampas. Ropelewski and Halpert (1987) found a tendency for enhanced precipitation in warm ENSO events during November and February of the following year. Ropelewski and Halpert (1989) reported below-normal precipitation during cold ENSO events: of the 19 cold events in the series they analyzed, 16 were associated with dry June–December seasons. Ropelewski and Halpert (1996) recently expanded their earlier results, but emphasized

shifts in the probability distribution of precipitation amounts. Pisciottano et al. (1994) analyzed ENSO-related changes in precipitation in Uruguay, a region geographically close to the Pampas. Tanco and Berri (1996) quantified the geographic extent of precipitation anomalies in the Pampas associated with ENSO.

Several studies have investigated the influence of ENSO-related climate variability on crop yields in Argentina. Garnett and Khandekar (1992) found that warm ENSO events appeared to favor Argentine winter wheat yields, whereas cold events tended to lower yields of this crop. Díaz (1995) explored associations between sea surface temperatures (SSTs) in the tropical Pacific Ocean (as indicators of ENSO conditions), rainfall anomalies, and yields of maize and soybean in key districts in the Pampas. Messina et al. (1996a) detected links between ENSO-related SST anomalies and wheat yields in four regions of Argentina. Messina et al. (1996b) showed significant correlation between Pacific SST anomalies in December and maize yields in the central part of the Pampas. Hansen et al. (1996) used biophysical crop models to study the effects of ENSO-related climate variability on the yields of wheat, maize, and soybean in three sites in the Pampas of Argentina. They showed improved net returns when crop management was modified in response to knowledge about ENSO phase.

In this work, long yield series (in some cases, approaching a century) for the major crops in the Pampas are used to explore the existence and nature of associations with ENSO phase. Crop yield data are detrended to remove effects of technological improvement, and yield anomalies are then computed. In subsequent sections, associations between yield anomalies and ENSO phase are explored through categorical analyses (contingency tables), and tests of differences in the central tendency and spread of yields among ENSO phases. Finally, a spatial summary of precipitation anomalies through the Pampas is derived through principal component analysis. These precipitation anomalies are then related to both ENSO phase and to crop yields.

2. Data

a. Crop Data

Records for the five major crops in Argentina (maize, wheat, sunflower, grain sorghum and soybean) were obtained from Argentina's Secretaría de Agricultura, Ganadería, Pesca y Alimentación (SAGPyA). Maize, wheat, and sorghum made up 91–93% of total production of cereals; soybean and sunflower accounted for 94–98% of oilseed production (in both cases, figures for 1987–1993; SAGPyA). Although data are aggregated at national level, the majority of the area and total production of these crops is in the Pampas. Production from the four Argentine provinces encompassing most of the Pampas (Buenos Aires, Córdoba, Santa Fe, and La Pampa) accounts for over 80% of the nation's production of sorghum, and over 90% for the other crops (average 1988–1992; data from NOAA-USDA Joint Agricultural Weather Facility). Except for limited areas (and only in recent years), the crops considered are grown without irrigation.

This work focuses on yield (estimated as the ratio of total production and area harvested) as an indicator of a crop's vulnerability to climate variability. Analyses of one winter crop (wheat) and four summer crops gives the opportunity of exploring potential consequences of ENSO-related variability at different times of the year. The time unit considered is the cropping cycle (or "agricultural year") between July and June of the following calendar year; under this definition both winter and summer crops fall within the same agricultural year. A cropping cycle is noted by the year in which the crop was sown, even though harvest may have taken place in the following

calendar year (e.g., the 1982/83 cropping season is noted as 1982). Table 1 shows the length of the yield series analyzed. Some earlier data were excluded because yields from very small sown areas were not considered representative. Table 1 also shows the number of cold and warm ENSO events (according to a definition presented below) and neutral years for each series.

b. Precipitation Data

Associations between crop yields and rainfall were explored using a database of monthly precipitation totals at 33 locations throughout the Pampas (Figure 1), encompassing the period 1912–1990. Data were originally compiled by the Argentine Meteorological Service, and were subject to quality checks before use.

c. ENSO Phase

An ENSO phase (warm, cold, or neutral) was assigned to each cropping cycle. There are several alternative definitions of ENSO events (Trenberth 1997b). Most definitions are based either on atmospheric pressure patterns (i.e., the Southern Oscillation Index, or SOI), on SST anomalies in the tropical Pacific Ocean, or a combination of both. Here, we categorized ENSO events according to an index developed by the Japan Meteorological Agency (JMA), which selects well the known events. The JMA ENSO index is based on a 5-month running mean of spatially averaged

Crop	Start	Length (years)	Warm	Neutral	Cold
Maize	1900	96	21	52	23
Wheat	1900	95 ^a	21	51	23
Sunflower	1932	64	12	37	15
Sorghum	1955	41	10	21	10
Soybean	1972	24	6	14	4

^a Wheat yield data missing for 1939/40 season.

Table 1. Country-wide crop data series for Argentina. The table shows the first cropping cycle and the length of each analyzed series; all series end in 1995. The number of warm and cold ENSO events and neutral years for each crop series is also shown.

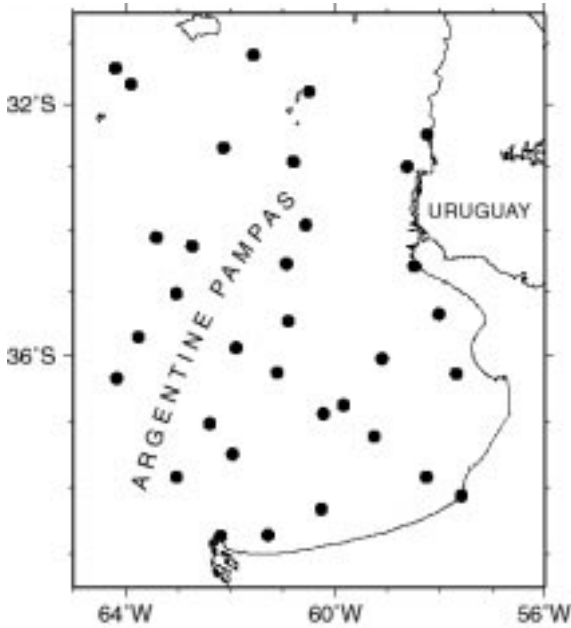


Figure 1. The study area. Black circles indicate location of rainfall stations.

SST anomalies in the region of the tropical Pacific Ocean between 4°N–4°S and 90°W–150°W (essentially the area known as “Niño-3”, although Niño-3 extends to ±5° latitude). If index values between July and June of the following year are 0.5°C or greater for at least six consecutive months (including the quarter October-December, considered as the typical peak of ENSO-related anomalies), the cropping cycle is categorized as an El Niño, or a warm event. Similarly, if the index is -0.5°C or lower for at least six consecutive months

(including October-December), the cycle is categorized as La Niña (or El Viejo, or a cold event).

The JMA index is based on observed data for the period from 1949 to the present. For years prior to 1949 (and going back to 1868), the index was derived from reconstructed monthly mean SST fields, estimated using an orthogonal projection technique (Meyers et al. in press). Identified ENSO events are listed in Table 2. For the period June 1900 to June 1996, the JMA definition identifies 21 warm events, 53 neutral years, and 23 cold events. The number of events for each crop changes with the length of the series; these numbers are shown in Table 1.

3. Crop Yield Trends and Anomalies

a. Low-Frequency Trends

Agricultural yield data typically have an upward low-frequency trend (LFT) due to technological improvements in crop genetics and management techniques (Hall et al. 1992). An LFT was fitted to the yield series using a non-parametric smoother called *loess* (not an acronym) (Cleveland and Devlin 1988). This technique has some advantages over approaches typically used in similar studies. First, *loess* does not make any *a priori* assumption about the shape of the trend, therefore it is flexible to follow any patterns suggested by the data. Second, its robust fitting procedure guards against outliers (unusually high or low yields) distorting the trend. A problem associated with the removal

ENSO Phase	Years
Warm	1902, 1904, 1905, 1911, 1913, 1918, 1925, 1929, 1930, 1940, 1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991
Cold	1903, 1906, 1908, 1909, 1910, 1916, 1922, 1924, 1938, 1942, 1944, 1949, 1954, 1955, 1956, 1964, 1967, 1970, 1971, 1973, 1974, 1975, 1988

Table 2. Warm and cold ENSO events between 1900 and 1995, as defined by the Japan Meteorological Agency index. Note that an “ENSO year” encompasses the period between July of the listed year, and June of the following year. For example, the warm event of 1982 includes the period between July 1982 and June 1983. Years not listed are considered as neutral.

of trends (although not unique to the use of *loess*) is that the estimated LFT also may reflect long-term climate effects. Conversely, the variability after removal of the trend may not be all climate-related.

When removing LFTs, one must decide on the desired degree of smoothing. The goal is to have a trend as smooth as possible, while capturing most of the significant behavior of the yields. Various degrees of smoothing were evaluated via graphic diagnostics, and results were all very similar. For the maize and wheat series, we used smoothing roughly equivalent to a low-pass filter with a cutoff frequency of about 40 years. For the shorter crop series, smoothing was adjusted to maintain a filter bandwidth somewhat similar to that of the longer series. The use of *loess* is illustrated in Figure 2, which shows maize yields and the fitted LFT.

Maize yields decreased from the early 1930s to the first half of the 1950s, coinciding with the well-described post-Depression “stagnation” of agriculture in the Pampas (Barsky 1988; Hall et al. 1992). In the 1950s, yields increased rapidly in response to the introduction of technological improvements such as maize hybrids, and fully mechanized labors and harvest (Obschatko 1988). There is no indication that the trend is leveling off, suggesting there is still room for improvement in the countrywide maize yields.

Low-frequency trends for all crops are shown in . The wheat LFT showed a steady increase between 1900 and the early 1970s, when yields increased

steeply with the introduction of Mexican germoplasm and the improvement of native cultivars (Gutiérrez 1988). Sunflower yields were relatively stable between 1932 and the mid-1970s, and then increased steeply in response to introduction of hybrids (Gutiérrez 1988). Sorghum showed relatively stable yields between 1955 and the mid-1960s, followed by a rapid yield increase. The increasing yield trend has not leveled, although the area sown with this crop has decreased substantially since the mid-1980s. The soybean LFT showed a rapid increase in yields between 1972 and 1980. Since then, yields have remained stable, despite huge expansion of this crop; the area harvested increased from about 157 000 ha in 1972 to about 5 910 000 ha (1 ha = 10 000 m²) in 1995, a 37-fold increase.

b. Absolute and Relative Yield Residuals

After LFTs were estimated, attention was focused on interannual variability in crop yields. Absolute yield residuals were computed for each crop by subtracting the LFT from the annual yields. We also computed relative yield residuals, defined as the ratio (as percentage) of the absolute residuals and the expected yield (the LFT) for a given year. Exploratory analyses produced qualitatively similar results with absolute and relative residuals. For ease of agronomic interpretation (as yields of all crops have

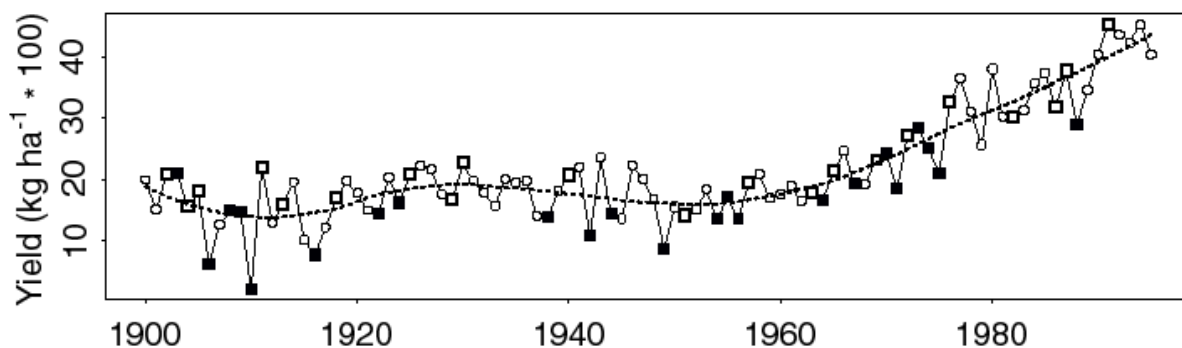


Figure 2. Time series of maize yields, 1900–1995. Open squares indicate warm ENSO events, filled squares correspond to cold events. Neutral years are shown as open circles. The dashed line indicates the estimated low-frequency trend.

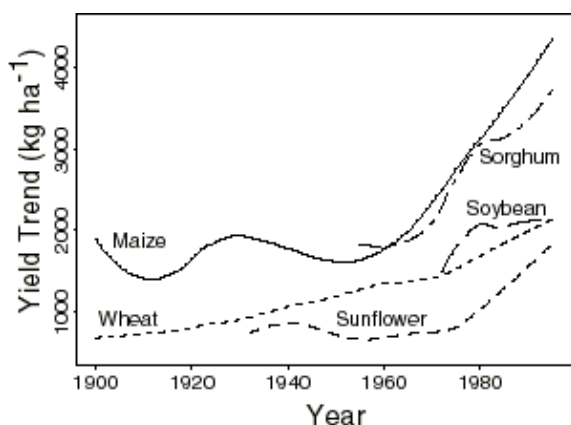


Figure 3. Low frequency trends for all crops.

changed significantly through the years), we present here results of analyses based on relative residuals. Unless stated otherwise, “residuals” or “anomalies” hereafter will refer to relative yield residuals. Descriptive statistics for absolute and

relative yield residuals are shown in Table 3. The years in which maximum and minimum yields occurred are noted, together with their corresponding ENSO phase. Interestingly, of the 20 extreme years listed, only three are neutral.

A topic of considerable debate in the agricultural literature is whether crop variability has increased or decreased in response to enhanced technology. For the series analyzed, changes in variability do not seem monotonic. Rather, epochs of high yield variability are detected, usually associated with a crop’s initial expansion (e.g., sorghum in the mid-50s), or with major changes in area sown (e.g., during the agricultural stagnation in the mid-30s to mid-40s).

4. Crop Yields and ENSO Phase

We explored associations between crop yield residuals and ENSO phase following two

	Maize	Wheat	Sunflower	Sorghum	Soybean
Minimum	-1185 (1910C)	-435 (1951C)	-272 (91W)	-729 (88C)	-439 (1988C)
	-84.4 (1910C)	-38.1 (1916W)	-31.4 (58N)	-25.3 (55C)	-21.0 (1988C)
33-percentile	-184	-52	-46	-89	-70
	-7.7	-4.9	-5.2	-3.9	-3.3
Median	56	-11	-5	-9	9
	2.6	-1.1	-0.7	-0.3	0.4
66-percentile	146	47	39	108	118
	6.9	4.7	5.1	3.5	5.7
Maximum	803 (1911W)	495 (1984N)	251 (1940C)	654 (1965W)	372 (1983N)
	57.7 (1911W)	35.2 (1964W)	29.6 (1940C)	36.1 (1957W)	18.3 (1983N)

Table 3. Descriptive statistics for yield residuals of all crops analyzed. The first row in each cell shows absolute residuals (in kg ha^{-1}). The second row of values in a cell shows relative residuals, expressed as percentage of the expected trend for any given year. The numbers in parentheses next to the maximum and minimum absolute and relative anomalies indicate the year in which these yield extremes occurred, as well as the corresponding ENSO phase (Warm, Neutral, or Cold).

approaches. First, we used contingency tables to detect associations between crop yields and ENSO phase. Then, we quantified differences among ENSO phases in central tendency and spread of yield anomalies.

a. Contingency Tables

We built a two-way contingency table for each crop (Tables 4a–e) by classifying each cropping cycle according to (i) ENSO phase (see Table 2), and (ii) yield residual tercile. The lower, middle and upper yield residual terciles included respectively the bottom, middle, and upper third of sorted residuals. Boundaries between terciles, the 33- and 66-percentiles, are shown for each crop in Table 3.

If there were no association between yields and ENSO, the number of years in each yield tercile for a given phase should be relatively similar. Furthermore, this number should be approximately equal to one third of the total number of events for that phase, as yields were divided into terciles. In contrast, deviations from expected frequencies would suggest that ENSO phase and crop yield categories are not independent. The statistical

significance of such deviations was assessed via χ^2 tests; results are shown in the bottom row of each table. An exact Fisher test was used when expected cell counts were low (< 5), and thus χ^2 results would be suspect.

As an example, let us examine the maize contingency table (Table 4a). There are 21 warm events in the maize series. Assuming no association with ENSO, there should be about seven years in each yield tercile. However, for the warm phase there are 13 years in the upper tercile. That is, high maize yields are almost twice as likely as by chance alone. Correspondingly, there are only three warm event years in the lower yield tercile, about half as many as would be expected. During cold ENSO events, the opposite pattern is observed. Given 22 cold events, one would again expect approximately seven years in each yield tercile. However, there are 16 years in the lower tercile, more than twice the number expected by chance alone. In contrast, only two cold events show yields in the upper tercile. The χ^2 p-value ($P \ll 0.001$) indicates that counts in the table cells are significantly different from those expected if

ENSO phase	Yield Terciles			TOTAL
	Lower	Middle	Upper	
Warm	3 (14)	5 (24)	13 (62)	21
Neutral	13 (25)	22 (42)	17 (33)	52
Cold	16 (70)	5 (22)	2 (9)	23
TOTAL	32	32	32	96
$\chi^2 = 24.520, df = 4, P \ll 0.001$				

Table 4a. Contingency table of maize yield residuals, 1900–1995, by yield terciles and ENSO phase. Results from a χ^2 test are listed at the bottom of the table. Row-wise percentage of years in each yield tercile is shown for each ENSO phase; values may not add to 100 because of rounding.

ENSO phase	Yield Terciles			TOTAL
	Lower	Middle	Upper	
Warm	7 (33)	5 (24)	9 (43)	21
Neutral	16 (31)	20 (39)	15 (29)	51
Cold	9 (39)	6 (26)	8 (35)	23
TOTAL	32	31	32	95
$\chi^2 = 2.574, df = 4, P = 0.631$				

Table 4b. Same as Table 4a, but

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ENSO phase	Yield Terciles			TOTAL
	Lower	Middle	Upper	
Warm	5 (42)	3 (25)	4 (33)	12
Neutral	13(36)	12 (32)	12 (32)	37
Cold	3 (20)	6 (40)	6 (40)	15
TOTAL	21	21	22	64

$\chi^2 = 1.741$, df = 4, P = 0.783. Exact Fisher test p-value = 0.808

Table 4c. Same as Table 4a, but for sunflower yield residuals, 1932–1995.

ENSO phase	Yield Terciles			TOTAL
	Lower	Middle	Upper	
Warm	1 (10)	4 (40)	5 (50)	10
Neutral	7 (33)	7 (33)	7 (33)	21
Cold	6 (60)	2 (20)	2 (20)	10
TOTAL	14	13	14	41

$\chi^2 = 5.662$, df = 4, P = 0.226. Exact Fisher test p-value = 0.245

Table 4d. Same as Table 4a, but for sorghum yield residuals, 1955–1995

ENSO phase	Yield Terciles			TOTAL
	Lower	Middle	Upper	
Warm	2 (33)	0 (0)	4 (67)	6
Neutral	2 (14)	8 (57)	4 (29)	14
Cold	4 (100)	0 (0)	0 (0)	4
TOTAL	8	8	8	24

$\chi^2 = 16.000$, df = 4, P = 0.003. Exact Fisher test p-value = 0.002

Table 4e. Same as Table 4a, but for soybean yield residuals, 1972-1995.

relative maize yields were independent of ENSO phase.

The wheat table (Table 4b) suggests a lack of association between ENSO phase and yield residuals. Because warm ENSO events may be associated with slightly higher than normal precipitation during the austral fall (Tanco and Berri 1996), we also examined a possible association between ENSO phase for a given year and wheat yield anomalies during the following cropping cycle. Such association might result, for example, from higher soil water contents prior to wheat's winter planting, due to ENSO-enhanced fall rains. A contingency table (not shown) linking ENSO phase

and wheat yield anomalies on the following year did not show any apparent association ($\chi^2 = 0.355$, P = 0.986). The sunflower and sorghum contingency tables (Tables 4c–d) show no significant overall association between ENSO phase and yields, whereas the association is significant for soybean (Table 4e).

The χ^2 test examines deviations from expected cell counts over an entire contingency table. However, we are particularly interested in departures from expected counts during extreme (warm and cold) ENSO phases. For example, how

unusual is the large number of years with high maize yields during warm events? The hypergeometric distribution provides a more specific test of such departures, and thus it was used to assess the probability of particular outcomes in the contingency tables.

In some cases (maize and soybean), the hypergeometric probabilities confirm the overall significance of the χ^2 tests for the contingency tables. For example, the probability of observing 13 years or more in the upper maize yield tercile during 21 warm events (given a total of 32 years in the upper tercile and 64 years in middle or lower terciles) was estimated to be 0.002. Conversely, the probability of observing 16 years or more in the lower maize yield tercile during 22 cold events is 0.0005. Therefore, maize yield departures from expected frequencies during both warm and cold events are highly significant. The soybean table (Table 4e) shows four upper-tercile years (twice the expected number) during warm ENSO events; this event has a probability of 0.069. At the same time, all four cold events fall in the lower yield tercile, a frequency with a probability of 0.007. That is, the effect of warm events on soybean is significant only at P levels of 0.07 or more, whereas cold events have a highly significant effect.

In other cases (sunflower and sorghum), interesting patterns emerge when attention is focused on extreme ENSO phases, even when the contingency tables show no significant overall association. For sunflower, the number of lower tercile residuals during cold events (three years) is about half what might be expected by chance; this outcome has a probability of 0.059. Low sunflower yields, thus, appear to be less likely during cold events than on other years. For sorghum, there is only one low-yield year (about three are expected) during warm events; the probability of getting one or less low-tercile years in warm events is 0.007. At the same time, the number of low-tercile years in cold events (six) is twice what would be expected by chance alone; the probability of observing at least this many years in this table cell is 0.029. As with maize, high yields (low yields) for sorghum are more frequent during warm (cold) events.

b. Central Tendency and Spread of Yields by ENSO Phase

The next stage in exploring associations between crop yields and ENSO phase was to quantify differences in the central tendencies and spread of

yield residuals among ENSO phases. Two estimators of the central tendency of yield residuals, the mean and median, are listed in Table 5 for each entire yield series and by ENSO phase. A Kruskal-Wallis test, a non-parametric analog of a one-way analysis of variance, was used to detect differences in the central tendency of residuals among *all* ENSO phases; *p*-values are listed in Table 6. One-tailed Wilcoxon tests were then used to examine differences in median yield residuals between *pairs* of ENSO phases (warm vs. neutral, neutral vs. cold, warm vs. cold); *p*-values for these tests are also listed in Table 6.

Although attention frequently is focused on the central tendency of yields, their spread or dispersion also is important for quantifying vulnerability to climate-related variability. Two estimators (Table 5) describe the spread of yield residuals. The first one is the standard deviation (SD). As outliers may influence the SD, a pseudo-standard deviation (SSD) is also presented as a resistant estimator of spread (Lanzante 1996). The SSD is computed by estimating the median absolute deviation (MAD) of residuals, and scaling it by a factor of 1.482 to make it a consistent estimator of the standard deviation for a Gaussian model (Wilks 1995). The significance of differences in the spread of yield residuals between pairs of ENSO phases was estimated via a test analogous to the parametric ratio of variances. The test statistic was the ratio of the squared SSDs for the two phases considered. Because the distribution of this statistic is unknown, we tested its significance through a randomization procedure (Manly 1997).

The central tendency of maize residuals was higher for warm events than for cold events, with neutral years falling in between (Table 5). Differences in both mean and median yields between warm and cold phases were over one fourth of the expected yields. Differences were highly significant for the neutral-cold and warm-cold phase pairs (Table 6), whereas the warm-neutral difference was significant only at probability levels of 0.10 or more. Mean and median wheat yield anomalies were similar for all ENSO phases, and no significant differences were detected. Mean and median sunflower yield anomalies were higher during cold events than during other ENSO phases. The difference between median (mean)

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Statistic	ENSO Phase			
	All	Warm	Neutral	Cold
<i>Maize</i>				
Mean	-0.51	9.03	3.31	-17.86
Median	2.64	11.38	3.57	-15.34
SD	20.58	15.58	15.75	24.43
SSD	18.76	9.46	15.96	13.93
N	96	21	52	23
<i>Wheat</i>				
Mean	0.07	-1.08	-0.01	1.32
Median	-1.13	-1.13	-0.89	-1.58
SD	14.28	15.88	13.88	15.22
SSD	12.74	16.71	13.09	10.43
N	95	21	51	23
<i>Sunflower</i>				
Mean	0.39	-0.69	-0.49	3.44
Median	-0.66	-5.05	-0.73	4.66
SD	11.95	14.03	11.64	11.22
SSD	11.10	12.17	11.36	6.46
N	64	12	37	15
<i>Sorghum</i>				
Mean	-0.02	8.13	1.10	-10.51
Median	-0.30	2.74	-0.87	-10.36
SD	13.92	14.79	11.61	11.99
SSD	7.19	3.76	7.47	16.72
N	41	10	10	21
<i>Soybean</i>				
Mean	0.16	4.41	2.70	-15.11
Median	0.44	8.80	1.42	-14.91
SD	11.55	12.61	8.91	6.03
SSD	12.58	9.99	6.81	7.41
N	24	6	14	4

Table 5. Estimates of central tendency and spread of yield residuals for an entire crop series, and by ENSO phase. The central tendency is described by the mean and the median. Estimates of spread are the standard deviation (SD), and a pseudo-standard deviation (SSD) computed from the median absolute deviation of residuals. N indicates the number of years in each ENSO phase.

residuals between cold and warm phases was about 10% (4%) of the expected yield, but these results showed no statistical significance. The central tendency of sorghum yield anomalies tended to be higher for warm events than for cold events. The magnitude of the differences between extreme phases ranged between 12 and 18% of expected yields, depending on whether means or medians were considered. As for maize, differences in yields were highly significant for the neutral-cold and warm-cold phase pairs, whereas the warm-neutral difference was significant only at

probability levels of 0.10 or more. Median yield residuals for soybean were higher during warm events than for cold events, with neutral years in between. Differences in median yields between extreme phases were of the order of 24% of expected yields. Both neutral-cold and cold-warm comparisons were highly significant; the warm-neutral test, in contrast, did not show significant differences.

For most crops, no significant differences were detected in the spread of yield residuals

	Maize	Wheat	Sunflower	Sorghum	Soybean
<i>Kruskal-Wallis test</i>	< 0.001	0.974	0.490	0.026	0.019
<i>Wilcoxon tests</i>					
Warm vs. neutral	0.083	(0.456)	(0.666)	0.078	0.301
Neutral vs. cold	< 0.001	(0.588)	(0.867)	0.027	0.001
Warm vs. cold	< 0.001	(0.546)	(0.814)	0.007	0.019
<i>Ratio of squared SSDs</i>					
Warm vs. neutral	0.037	0.474	0.852	0.245	0.467
Neutral vs. cold	0.661	0.577	0.094	0.159	0.946
Warm vs. cold	0.121	0.311	0.270	0.058	0.731

Table 6. Probability values of (a) Kruskal-Wallis tests of differences in central tendencies of yield residuals between all ENSO phases, (b) one-tailed Wilcoxon tests of differences in central tendencies of yield residuals between pairs of ENSO phases, and (c) tests of differences in spread of yield residuals between pairs of ENSO phases. For this last set of tests, the statistic was the ratio of squared pseudo-standard deviations, and significance was estimated via a randomization procedure. P-values in parentheses for the wheat and sunflower Wilcoxon tests indicate lack of significance in central tendency among all ENSO phases, as indicated by the Kruskal-Wallis tests.

between ENSO phases. The only significant result (at a level of 0.05) was the lower spread of maize residuals during warm events, when compared to that of neutral years.

5. Yield and Precipitation Anomalies

Previous sections established significant statistical associations between yields of some crops in the Pampas and ENSO phase. However, the factors that might mediate these associations have not been discussed so far. There is considerable evidence that ENSO influences precipitation regimes in the Pampas (see Introduction). Furthermore, in many parts of the world rain-fed crop yields are tied to available soil water and precipitation. For these reasons, in this section we focus on associations between precipitation and crop yield residuals in the Pampas.

Precipitation anomalies throughout the Pampas were summarized via principal component analysis (PCA), a useful technique for extracting information from multi-dimensional data sets (Wilks 1995). Analyses were based on monthly precipitation totals at 33 stations for the period 1912–1990 (Figure 1).

PCA is typically conducted on centered data or anomalies (Wilks 1995). As a first step, we removed the seasonal cycle of precipitation to work with precipitation residuals. Significant low-frequency rainfall fluctuations have been reported in the Pampas (Barros et al. 1996; Dai et al. 1997). These changes, however, appear to have occurred mostly during summer months (Hurtado et al. 1996). A flexible technique called STL (Seasonal Trend decomposition based on Loess; Cleveland et al. 1980) allowed the seasonal cycle of precipitation to change on time scales of several years, while simultaneously estimating a low-frequency component. This approach effectively dealt with trends concentrated in specific times of the year. Detailed results from the seasonal decomposition are beyond the scope of this paper. Subsequent analyses focused on precipitation residuals, computed by subtracting from the original precipitation series the seasonal and low-frequency components (estimated separately for each station).

To reduce intra-annual variability, monthly precipitation anomalies at each station were aggregated over 3-month overlapping periods. For each 3-month series, principal component

decomposition was carried out on the correlation matrix of precipitation anomalies. We focus on results for three series, centered on November, December, and January (the series will be noted as OND, NDJ, and DJF, indicating the months they encompass). The first principal component accounted for 46.5%, 44.5% and 41.1% of total variability in the OND, NDJ, and DJF series, respectively.

The time series of the first principal component (PC1, also referred to as amplitudes or scores; Wilks 1995) can be viewed as an optimally weighted average (where the weights are estimated through the PCA) of precipitation anomalies for all stations. Therefore, the PC1 series summarizes in a single time series the temporal evolution of precipitation anomalies over the Pampas. Further, this approach drastically reduces effects of possible inhomogeneities or erroneous values in the original data series (Widmann and Schär 1997). The PCA provides other useful results (e.g., spatial patterns of precipitation fluctuations), but these will not be discussed here.

There is a distinct association between ENSO phase and precipitation anomalies in the Pampas during November–January, as illustrated by a boxplot of PC1 amplitudes by ENSO phase (Figure 4). Although PC amplitudes have no physical units and their signs are arbitrary, in this case positive values indicate positive precipitation anomalies, and vice-versa. Warm ENSO events clearly are associated with higher median precipitation anomalies than neutral and cold events, in that order. Furthermore, the spread of anomalies is much smaller during cold events. Boxplots for the OND and DJF series (not shown) reveal similar patterns. These results agree with previous reports of a strong ENSO signature in the study region during late spring and early summer (e.g., Ropelewski and Halpert 1996).

To explore associations between precipitation and yield anomalies, PC1 amplitudes for the OND, NDJ, and DJF series were correlated with each of the summer crop series. Figures 5a–d show scatterplots of yield residuals for maize, sunflower, sorghum, and soybean, as a function of PC1 amplitudes for the NDJ series. A *loess* fit is shown (solid line) to facilitate visualization of trends. The strength of the associations was quantified via the rank-based Spearman correlation coefficient (ρ). This statistic reflects monotonic associations between two variables, even if the associations are

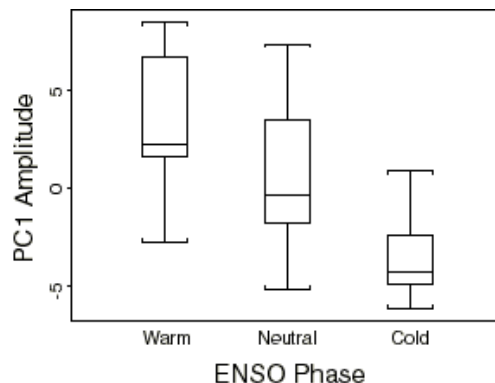


Figure 4. Boxplot of PC1 amplitudes for November–January, by ENSO phase. Lower and upper boundaries for each box are the 25- and 75-percentiles; that is, the box encompasses the central 50% of the data for each phase. The line inside each box indicates the median. Whiskers mark the range of the values.

non-linear (as is typically the case with crop and climate variables).

The association between national-level maize yield anomalies and precipitation anomalies throughout the Pampas is remarkably tight (Figure 5a): low precipitations (negative PC1 values) are associated with low maize yields, and vice-versa. The fitted trend line suggests a progressively decreasing effect of positive precipitation anomalies on yields, possibly as other factors become limiting. The close association is confirmed by a highly significant correlation ($\rho = 0.816$; $P < 0.001$). The other precipitation series show similar patterns of association with maize yields, but correlations are lower (albeit still highly significant): ρ values are 0.580 and 0.561 for OND and DJF, respectively. Sunflower yield shows a rather flat response to precipitation (Figure 5b), and no significant correlation is detected. For sorghum, the yield-precipitation association (Figure 5c) is similar to that of maize, although correlation values are generally lower. The highest correlation ($\rho = 0.497$; $P = 0.009$) occurs in DJF, a month later than for maize. Correlation values for OND and NDJ are 0.235 ($P = 0.199$) and 0.395 ($P = 0.034$). For soybean, yields have a different behavior when NDJ precipitation anomalies are negative or positive (Figure 5d). While anomalies are negative, yields tend to

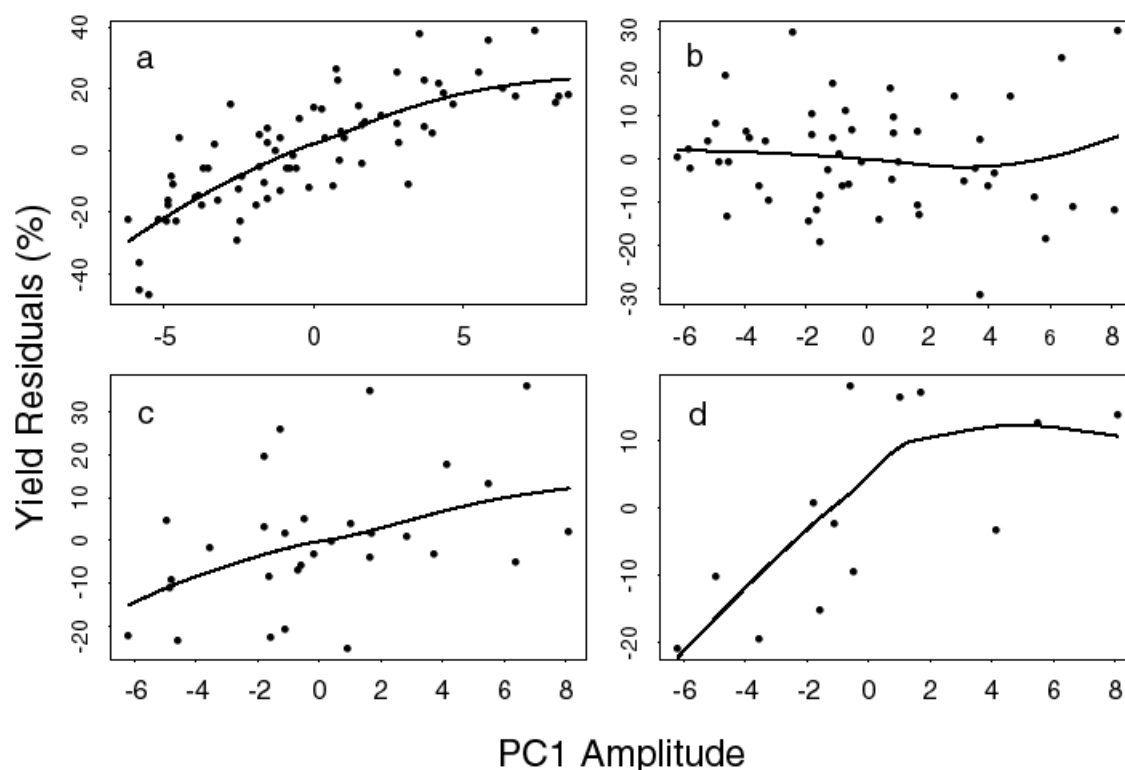


Figure 5. Yield anomalies for summer crops as a function of PC1 amplitudes for the November–January series. Negative PC1 amplitudes indicate negative precipitation anomalies, and vice-versa. Figure panels correspond to (a) maize, (b) sunflower, (c) sorghum, and (d) soybean.

increase with precipitation. In contrast, for positive precipitation anomalies soybean yields are mostly positive, but they do not increase with increasing precipitation (the fitted trend line is rather flat for this portion of the graph). A similar pattern is present in the OND and DJF series (not shown). Correlations for the OND, NDJ and DJF series are 0.726, 0.665, and 0.643, and they are all significant (corresponding p-values are 0.008, 0.022, and 0.034).

6. Discussion

We explored associations between yield anomalies of major grain crops in Argentina and ENSO phase using various complementary approaches. Although high and low yields have occurred under all ENSO phases, most crops considered show some degree of association with ENSO. For maize and sorghum, there is a tendency towards higher (lower) yields during warm (cold) ENSO events. In

both crops, the depression of yields during cold events is, on average, larger and more consistent than yield increases during warm events. A decrease during cold events is also observed in soybean yields, although there does not seem to be a significant corresponding effect of warm events. For sunflower, the overall association with ENSO is not significant, although cold events appear to be more favorable. Finally, wheat, the only winter crop considered in this work, did not show any association with ENSO. These summarized conclusions are expanded in subsequent paragraphs.

Maize yields show the clearest association with ENSO. During warm events, high yields (above 7% of expected value) are almost twice as likely as expected by chance alone. The opposite pattern occurs during cold events: the number of years in the lower third of the historical yield distribution (below -8% of

expected yield) is more than twice what would be expected by chance. Even though maize shows the tightest association with ENSO, we remind readers that yield anomalies as low as -12.5% and as high as 26.8% have respectively occurred during the apparently favorable (unfavorable) warm (cold) ENSO events. A similar caveat can be made for the other crops studied.

Ties between maize yields and ENSO phase are probably mediated by the enhanced likelihood of higher (lower) than normal rainfall during late spring-early summer, typical of warm (cold) ENSO events. December precipitation and soil moisture in December-January are important in determining maize yields in Argentina (Rebella et al. 1984). Response to nitrogen fertilization in the highest-quality lands of the Pampas is strongly related to rainfall during December and January (Hall et al. 1992). These months encompass the maize flowering period throughout the Pampas. This period is critical in defining corn yield, and sensitivity to water availability is extremely high (Hall et al. 1981). In turn, the late spring-early summer period coincides with a strong ENSO-related precipitation signal over central-eastern Argentina (Ropelewski and Halpert 1987, 1989, 1996). The important role of precipitation was confirmed by the tight association between maize yields and an index of November–January precipitation anomalies in the Pampas (Figure 5a). Furthermore, this index showed a clear association with ENSO phase (Figure 4).

The clear associations found here between both maize yields and ENSO phase, and between yields and precipitation anomalies, differ from some literature reports. Díaz (1995) found extremely low correlation between rainfall and maize yield anomalies in four major districts in Argentina. Differences in results may be due to the length of the data series, or the spatial scale of the analyses. Links between rainfall and yields frequently show substantially higher variability at a district level than at a national level (Dilley 1997). Díaz (1995) also found rainfall anomalies to be more closely related with national-level maize production than with yield anomalies. He attributed this effect to higher spring rains encouraging farmers to sow maize even in areas with higher climate risks, with consequently higher total production; yields, however, could be higher or lower.

Soybean, currently the most important summer crop in Argentina, shows a significant association with the cold ENSO phase. All four cold events

(admittedly, a small number) in the short soybean series showed yields in the lower tercile (below -3% of expected yield). The difference in median yields between warm and cold phases is of the order of 24% of expected yields. Soybean shows an interesting response to precipitation. There is a clear association between negative precipitation anomalies and soybean yields: lower precipitation results in lower yields. In contrast, yields, while mostly high, seem to become relatively insensitive to precipitation when positive anomalies occur. This suggests that once the minimum water needs of the crop are satisfied, yields reach a maximum, the level of which may be defined by other limiting factors. A similar pattern was observed in a simulation of soybean growth under various irrigation levels by Hoogenboom et al. (1991).

The associations between sorghum yields and both ENSO phase and precipitation anomalies are similar to those for maize. However, correlation between precipitation and yield is lower than for maize, as sorghum is generally more resistant to water stress. For example, sorghum is able to modify its maturity in response to water availability: if there is water stress, the crop may delay its reproductive stage for short periods (Whiteman and Wilson 1965). The result may be a somewhat lower sensitivity of sorghum yields to water shortages.

Sunflower yields do not show an immediately apparent association with ENSO phase, as indicated by the lack of significance of most tests performed here. There is, however, a tendency for high yield residuals to be more frequent during cold events, a pattern opposite to that of the other summer crops considered. Because of its deep rooting system, water shortages frequent during cold ENSO events may not affect sunflower as much as other crops (Connor and Sadras 1992). In contrast, enhanced precipitation during warm events may favor the spread of diseases such as *Sclerotinia*, or loss of nitrogen through leaching, with a consequent decrease in yields. Furthermore, factors other than precipitation may play a significant role: solar radiation, for example, may influence the number of grains, and thus sunflower yields (Cantagallo et al. in press). The association between ENSO and this climatic variable,

however, has not been documented in the region so far.

Wheat, the single winter crop considered here, does not show any apparent associations with ENSO phase. Water availability during the early part of this crop's cycle (from planting to pre-flowering) is tied to yield variability (Magrin 1990). For example, about 42% of wheat yield variability in the best lands of the Pampas has been linked to water availability in September-October (Hall et al. 1992). Nevertheless, the ENSO signature in winter-early spring is more variable than later in the spring. Another factor that may cause the apparent lack of association with ENSO is the wide geographic distribution of wheat. As a consequence, regionally inhomogeneous ENSO effects may cancel out when analyzing national-level yields. More importantly, because of the crop's wide distribution, timing of critical periods varies with latitude. For example, in the southern Pampas, November is a critical period for wheat, as flowering tends to occur in the second half of the month (Travasso 1990). This month shows a clear ENSO signal, and therefore preliminary analyses show clearer associations with wheat yields in the southern Pampas than at national level.

At first glance, it may appear surprising that clear patterns of association emerge between national-level crop yields and climate variability, as one might expect a dampening effect of spatial aggregation. Nevertheless, large-scale associations between crop yields and climate anomalies have been previously established, for example, over the continental United States (Mostek and Walsh 1981). Furthermore, Mostek and Walsh (1981) found these associations to account for fractions of total variance comparable to studies conducted at local and statewide levels.

For many of the crops showing associations with ENSO, cold events appear to have stronger, more consistent effects than warm events. Yield decreases associated with cold events are usually larger (and often less variable) than corresponding yield increases during warm events. On one hand, this may reflect a stronger effect of cold ENSO events on the regional climate. Indeed, Ropelewski and Halpert (1996) found the association between rainfall anomalies and the cold phase to be stronger than for warm events in this region. Tanco and Berri (1996) also stressed the importance of cold events, as the below-normal rainfall associated with this ENSO phase showed a larger

areal extent and persisted longer than the impacts of warm events. Therefore, although much attention has been given in this region to the consequences of El Niño, future studies should not neglect the effects of the potentially more damaging Niña events.

On the other hand, the relative effects on crop yields of warm and cold ENSO events may have been distorted by the relatively low level of input usage that prevailed in Argentine agriculture until the 1990s. Low-input agricultural systems may realize only a small portion of the yield potentially achievable under favorable conditions tied to warm events (Baethgen, personal communication). The diminishing effects of high precipitation anomalies on maize yields (Figure 5a) suggest that potential yields during warm events are not being fully exploited, and there is an opportunity for yield increases through increased inputs. In the last few years, agricultural production systems in Argentina have changed radically: fertilizer and agrochemical usage has increased significantly. It should not be surprising, therefore, if the effects of warm ENSO events on crop yields become more marked in the future. For instance, as a consequence of the strong 1997 ENSO event, all-time record maize yields are expected in Argentina.

Although this work has considered only associations between ENSO and crop yields, a more complete characterization of ENSO effects also should involve an assessment of the impacts on economic performance of the crop enterprise. For example, Phillips et al. (1996) explored ENSO effects on farm-level profits and risks in the US Corn Belt. They found that only 14% of El Niño years were associated with economic losses for maize, whereas 33% of La Niña years showed losses. A characterization of economic effects of ENSO on Argentine agriculture is the topic of follow-up work.

Results presented here may be relevant to a broad range of decision makers in the agricultural sector. Individual farmers may consider our findings to gauge risks associated with ENSO events, and as input to decision making about alternative management in response to forecasted ENSO events (e.g., fertilizing maize during El Niño years). Differences in variability, however,

must be kept in mind when extrapolating national-level results (as shown here) to district or even individual enterprise scales. Given Argentina's significant participation on the global maize and soybean markets, traders in Argentina and elsewhere might make better projections of aggregated supply conditions for a crop, which in turn may determine the market price (Mjelde et al. 1997). As in other parts of the world (Smit et al. 1997), there is currently a trend in Argentina towards government shifting some of the climate-related risks to individual farmers. Agricultural emergency laws are currently under review, and crop insurance will probably become more common in the future. For these reasons, public sector policy makers may benefit from quantitative information on potential impacts of ENSO.

Turning skillful but uncertain ENSO-related climate forecasts into useful information and beneficial decisions is a major challenge for the immediate future (Trenberth 1997a). A necessary step towards the adoption and effective use of climate forecasts in agriculture is a characterization of the impact of ENSO. If there is no ENSO signal on crop yields or economic returns in a region, it is unlikely agricultural stakeholders will benefit from the forecasts (unless one considers impacts on other world producers of the commodity, which may influence output prices). However, we stress that simply documenting that ENSO affects yields does not imply that the agriculture sector will benefit from the adoption of climate forecasts. For forecasts to have beneficial effects on this sector, and on society in general, they must induce changes in the decision making process, and on the actions taken by sector agents (Sonka et al. 1987; Hammer et al. 1996). Our work has shown a significant impact of ENSO on yields of many crops in Argentina. Such impacts, most likely, will also be present in economic returns. Findings similar to ours, therefore, may provide a meaningful incentive for farmers to adopt the more complicated flexible management required to take full advantage of climate information.

Acknowledgments. This work was supported by grants from the National Oceanic and Atmospheric Administration (Office of Global Programs) and the National Science Foundation (Methods and Models for Integrated Assessment Initiative) to a Consortium of Florida Universities (University of Miami, Florida State University, University of Florida). The Inter-American Institute for Global Change Research (IAI) provided additional funding

as part of its Initial Science Program. C. Messina and M. Grondona conducted part of the research during IAI Fellowships at the Univ. of Miami. Drs. J.J. O'Brien and D. Legler (Center for Ocean and Atmosphere Prediction Studies, Florida State University) kindly provided the JMA SST anomalies. Helpful comments by Drs. J. Hansen and J. Jones are gratefully acknowledged.

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