Economic Implications of Potential Climate Change Induced ENSO Frequency and Strength Shifts

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Abstract

Some argue that global climate change may alter the frequency and strength of extreme events. This paper examines the economic damages in the agricultural sector arising from a shift in El Niño Southern Oscillation(ENSO) event frequency and strength. The assumptions about the frequency of ENSO shift are motivated by an April, 1999 Nature article by Timmermann *et al.* (1999). The damage estimates reported here are in the context of the global agricultural system. Annual damages in the $3 to 4 hundred million U.S. dollar range are found if only the frequency of ENSO events changes. However, annual damages rise to over $1 billion if the events also intensify in strength. Event anticipation and crop mix adaption on the part of farmers can help offset the damages but cannot fully alleviate them.

Economic Implications of Potential ENSO Frequency and Strength Shifts

Some argue that global climate change may alter the frequency and strength of extreme events. One marker for extreme events that has recently received considerable public attention is the El Niño-Southern Oscillation(ENSO) climatic phenomenon. Timmermann *et al.* (1999) recently presented results from a modeling study implying that global climate change would alter ENSO characteristics causing

- the mean climate in the tropical Pacific region to change towards a state corresponding to present day El Niño conditions;
- stronger inter-annual variability with more extreme year-to-year climate variations
- more skewed inter-annual variability with strong cold events becoming more frequent.

This paper explores the economic implications of a shift in ENSO frequency and intensity using the quantitative definition of the shift as developed by Timmermann *et al*. Specifically, this paper estimates the economic consequences of shifts in ENSO frequency and strength on the world agricultural sector. These economic consequences include changes in consumers and producers welfare as well as trade surplus.

Background on ENSO Effects on Agriculture

The ENSO is a pervasive climate phenomena which has been found to be associated with regional climate variations throughout the world. There are three phases: warm-El Niño, cold-La Niña and other (non El Niño or La Niña), generally referred to as Neutral. Changes in ENSO event frequency and strength may already be occurring. Gammon (1999) argues that before 1976, La Niña and El Niño events occurred with about the same frequency, but that subsequently, their frequency has become irregular. Quinn and Niell(1987) pointed out that a strong ENSO event occurred every 42-45 years during the period from 1525 to 1983 but that recently stronger El Niños appear to be occurring more frequently (1982 and 1997).

ENSO events have been found to influence regional weather and, in turn, crop yields (Nicholls, 1986; Legler *et al.*, 1999). Changes in crop yields have obvious economic implications. Several studies have estimated the value of farmers adapting to ENSO events; results indicate that there is economic value to the agricultural sector in using information on ENSO events. In terms of aggregate U.S. and world economic welfare, the estimates of using ENSO information in agricultural decision making have been in excess of $300 million annually (e.g., Solow *et al.* (1998) - $323 million, Chen and McCarl(1999) -$450 million). Mjelde *et al.* (1997) and Marshall *et al.* (1996) examined farm level implications and found substantial gains to producers. Such estimates imply that a shift in ENSO event frequency or strength may carry substantial economic consequences. Other studies have shown that the economic damages to U.S. agriculture from a severe ENSO event can exceed several billion dollars (Adams *et al.*, 1999).

ENSO Event and Strength Shifts under Climate Change

According to Timmermann *et al.*, the current probability of ENSO event occurrence (with present day concentrations of greenhouse gases) is 0.238 for the El Niño phase, 0.250 for the La Niña phase, and 0.512 for the Neutral (non El Niño - non La Niña) phase. They then project that the probabilities for these three phases will change under increasing levels of greenhouse gases assumed under IPPC (IPPC, 1992) scenario IS92a*. Under such a scenario, ENSO event

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*This ENSO probability shift is calculated from Timmermann *et al.*'s Figure 4 which displays the frequency of occurrences of SST anomalies. Cases with their SST anomaly index below -0.5^{o}C were classified as La Niña while above 0.5^{o}C were classified as El Niño.

frequency is forecast to become 0.339, 0.310, and 0.351 for El Niño, La Niña and Neutral, respectively. Thus, the frequency of both the El Niño and La Niña phases are expected to increase, while the Neutral phase frequency would be reduced. While not offering specific evidence, they argued that such a frequency change could be expected to have strong ecological and economic effects.

Framework for Estimation of the Economic Effects of ENSO Frequency Shifts

The economic consequences of ENSO frequency shifts will be measured using the same basic approach as in Solow *et al.* (1998) and as expanded on by Chen and McCarl (1999). In particular, a model is used which simulates production, acreage allocation and consumption based on a stationary joint probability distribution of yields for 10 crops in 63 U.S. and 28 world regions from 1972 to 1993 (Chen and McCarl, 1999). These 22 years are then grouped into the three ENSO phases, with five events during the period classified as El Niño and four as La Niña. In turn, a stochastic, mathematical programming model of the U.S. agricultural economy is used to estimate the consequences of such events in terms of the welfare of consumers and producers**. That model is constructed to select crop mixes (proportions of acreage devoted to specific crops) before weather characteristics are known but simulates market clearing prices and consumption after production is realized. The modeling components of this framework are discussed in the next section.

**Detailed descriptions of the model characteristics are provided in Chen and McCarl (1999).

Empirical Model of the Agricultural Sector

An empirical model of the U.S. agricultural sector(hereafter called ASM) forms the core of the stochastic model. ASM is based on the work of Baumes (1978) which was later modified and expanded by Burton and Martin(1987); Adams *et al.* (1986); Chang *et al.* (1992) and Lambert *et al.* (1995).

Conceptually, ASM is a price endogenous, mathematical programming model of the type described in McCarl and Spreen (1980). Constant elasticity curves are used to represent domestic consumption and export demands as well as input and import supplies. Elasticities were assembled from a number of sources including USDA through the USMP modeling team (House, 1987) and prior model versions.

ASM is designed to simulate the effects of various changes in agricultural resource usage or resources available on agricultural prices, quantities produced, consumers' and producers' welfare, exports, imports and food processing. In calculating these effects, the model considers production, processing, domestic consumption, imports, exports and input procurement. The model distinguishes between primary and secondary commodities with primary commodities being those directly produced by the farms and secondary commodities being those involving processing.

Within ASM, the U.S. is disaggregated into 63 geographical production subregions. Each subregion possesses different endowments of land, labor and water as well as crop yields. Agricultural production is described by a set of regional budgets for crops and livestock. Marketing and other costs are added to the budgets following the procedure described in Fajardo *et al.*(1981) such that the marginal cost of each budget equals marginal revenue. ASM also contains a set of national processing budgets which uses crop and livestock commodities as inputs (USDA, 1982). There are also import supply functions from the rest of the world for a number of commodities. The demand sector of the model consists of the intermediate use of all the primary and secondary commodities, domestic consumption use and exports.

There are 33 primary crop and livestock commodities in the model. The primary commodities depict the majority of agricultural production, land use and economic value. The model incorporates processing of the primary commodities. There are 37 secondary commodities that are processed in the model. These commodities are chosen based on their linkages to agriculture. Some primary commodities are inputs to the processing activities yielding these secondary commodities and certain secondary products (feeds and by-products) are in turn inputs to production of primary commodities.

Three land types (crop land, pasture land, and land for grazing on an animal unit month basis) are specified for each region. Land is available according to a regional price elastic supply schedule with a rental rate as reported in USDA farm real estate statistics. The labor input includes family and hired labor. A region-specific reservation wage and maximum amount of family labor available reflect the supply of family labor. The supply of hired labor consists of a minimum inducement wage rate and a subsequent price elastic supply. Water comes from surface and pumped ground water sources. Surface water is available at a constant price, but pumped water is supplied according to a price elastic supply schedule.

U.S. agricultural sector models typically only deal with aggregate exports and imports facing the total U.S. without regional trading detail. To reasonably portray ENSO effects we introduce multiple foreign regions, and shipment among foreign regions by including spatial equilibrium models for the major traded commodities (Takayama and Judge, 1971). To portray U.S. regional effects, U.S. markets are grouped into the ten regional definitions used by the USDA. We also added variables for shipment among U.S. regions, and shipment between U.S. regions and foreign regions.

The commodities subject to explicit treatment via the spatial equilibrium world trade model components are hard red spring wheat (HRSW), hard red winter wheat (HRWW),soft red winter wheat (SOFT), durum wheat (DURW)), corn, soybeans and sorghum. These commodities are selected based on their importance as U.S. exports. The rest of the world is aggregated into 28 countries/regions. Transportation cost, trade quantity, price and elasticity were obtained from Fellin and Fuller (1998), USDA (1987) statistical sources and the USDA SWOPSIM model (Roningen, 1986).

Conceptual Stochastic Model

Regional crop yields vary by ENSO phase and event strength. Knowledge of yield outcomes (with or without ENSO events) is imperfect when agricultural planting decisions are made. Therefore, the modeling framework includes a yield distribution (following the modeling approach explained in Lambert *et al.*, 1995). At the time of planting a number of yield states of nature can occur but the farmer does not know which one will occur. In fact, farmers must choose crop mix considering the weather probability distribution without knowledge of which exact weather event will occur. The stochastic modeling framework depicts this using a two stage formulation as in Dantzig (1955); Cocks (1968); McCarl and Parandvash (1988); Lambert *et al.* (1995) or Solow *et al.* (1998).

The analysis used here differs from the Solow *et al.* (1998) and Adams *et al.* (1995) analyses (which used essentially the same model) in terms of the way ENSO events are incorporated and the way that the El Niño event is valued. Namely, in the prior work, a three state definition of ENSO phase was used for the stochastic outcomes (El Niño, La Niña and Neutral). Here we do not use ENSO phase in defining possible states or stochastic outcomes but rather define states for each of 22 historically observed years on which we have data (1972-1993). This allows us to model changes in both ENSO frequency and strength.

An Algebraic Representation of the Modeling Framework

Overall, the model framework is summarized by the following equations. The objective function is:

$$
\begin{aligned}
(1)\ \text{Max:}\quad & - \sum_{j} \sum_{k} C_{jk} X_{jk} - \sum_{k} \sum_{r} \int ''(R_{rk}) dR_{rk} \\
& + \sum_{s} P_s ([\sum_{i} \int n(Q_{is}) dQ_{is} \\
& + \sum_{i} \sum_{c} \int (FD(FQD_{ics}) - FS(FQS_{ics})) dTQ_{ics} \\
& - \sum_{i} \sum_{k} \sum_{c} USFTRD_{i,c,k,s} USFCST_{i,k,c} \\
& - \sum_{i} \sum_{c} \sum_{c1} FTRD_{i,c,c1,s} FFCST_{i,c,c1} \\
& - \sum_{i} \sum_{k} \sum_{k1} USTRAN_{i,k,k1,s} USCST_{i,k,k1} \\
& - \sum_{i} \sum_{k} PDIF_{ik} (TN_{iks}]
\end{aligned}
$$

where

i indexes commodities,

j	indexes production process,
k,k_1	indexes U.S. regions ,
c,c_1	indexes ROW regions,
r	indexes resources,
s	indexes ENSO phase,
Ps	probability of ENSO phase s,
Q_{is}	consumption of i^{th} product in ENSO phase s,
FQD_{ics}	excess demand quantity in ROW region c for commodity i and ENSO phase s,
FQS_{ics}	excess supply quantity in ROW region c for commodity i and ENSO phase s,
R_{rk}	resource supply for U.S. region k of resource r,
n(Q_{is})	inverse U.S. demand function for commodity i consumed under ENSO phase s,
"(R_{rk})	inverse U.S. factor supply function for resource r in region k,
$FD(FQD_{ics})$	inverse excess demand function in importing ROW region c,
$FS(FQS_{ics})$	inverse excess supply function in exporting ROW region c,
C_{jk}	cost of j^{th} production process per acre in U.S. region k,
X_{jk}	acreage of j^{th} production process in U.S. region k,
$FTRD_{icc1s}$	trade between ROW regions c and c1 of commodity i for ENSO phase s,
$USFTRD_{icks}$	trade between ROW region c and U.S. region k of commodity i for ENSO phase s,
$USTRAN_{ikk1s}$	shipment between U.S. regions k1 and k of commodity i for ENSO phase s,
$FFCST_{icc1}$	transportation cost from ROW regions c and c1 for commodity i,
$USFCST_{ikc}$	transportation cost from U.S. region k to ROW region c for commodity i,
$USCST_{ikk1}$	transportation cost between U.S. regions k1 and k for commodity i,
$PDIF_{ik}$	price difference between U.S. region k and U.S. national market for commodity i,
TN_{iks}	U.S. national consumption of commodity i from U.S. region k for ENSO phase s.

This set of relationships blends the spatial equilibrium world trade model and the price endogenous model of the U.S. agricultural sector (ASM). In particular, the first two lines include terms typically found in the conventional sector model, i.e., they represent the area under the U.S. national demand equations (IR(Q_{is}) d Q_{is}) for commodity i less the area under the regional (k) factor supply curves incorporating the perfectly elastic production costs associated with production process j ($C_{jk}X_{jk}$) and the quantity dependent (I"$(R_{rk}$) d R_{rk}) prices for factor r. The next four lines are the spatial equilibrium world trade model with line three giving the area under the ROW excess demand curves minus the area under excess supply curve for commodity i in region c. Line four sums the transportation costs times the volume traded between the U.S.

regions and the foreign regions for US imports and exports (USFTRD). Line five sums the transportation costs times the volume traded among the foreign regions (FTRD). Line six sums the transportation costs between regions in the U.S.(USTRAN). The last line is the price difference between U.S. regions and the U.S. national market times the shipment quantity. This variable (TN) is incorporated into the model to carry regional supply to national demand in order to balance the national market.

The model is stochastic in that all terms and variables but those in the first line are state of nature dependent. This assumes that production and factor use are set before the ENSO state of nature is known, but that demand and trade are set afterward (as explained in Lambert *et al.*). The second line multiplies by probability. This renders the objective function a maximization of expected welfare.

The model contains commodity balances in the U.S. as follows

(2)
$$
\begin{aligned}
& -\sum_{j} ((Y_{ijk}+YR_{ijks})(X_{jk}) - \sum_{c} USFTRD_{i,c,k,s} - \sum_{k1} USTRAN_{i,k1,k,s} \\
& + \sum_{c} USFTRD_{i,k,c,s} + TN_{iks} + \sum_{k1} USTRAN_{i,k,k1,s} \le 0 \qquad \text{for all } i,\ k,\ s.
\end{aligned}
$$

where supply from normal or average production (Y) plus the difference due to ENSO phase event (YR) times acreage (X) plus that imported from other U.S. (USTRAN) and world (USFTRD) regions is balanced against exports to other U.S. (USTRAN) and world regions (USFTRD) as well as movements into domestic demand (TN) for a commodity (i) in a region (r) under ENSO phase event (s).

There is also a national commodity balance constraint in the U.S.

(3) $$Q_{is} - \sum_{k} TN_{iks} \le 0, \qquad for\ all\ i,\ s.$$

where aggregate demand (Q) is balanced with the quantities (TN) from the regions (k) by commodity (i) and state of nature(s).

The factor constraint for region k in the U.S. is

(4) $$\sum_{j} f_{rjk} X_{jk} - R_{rk} \le 0, \qquad for\ all\ k,\ r$$

where f_{rjk} is the resource usage per acre for jth production processing in region k for resource r. This equation balances factor supply (R) against usage by production (fX) in region k for factor r.

The commodity balance constraint for good i in ROW region c is

(5) $$\begin{aligned} &+FQD_{ics} + \sum_{k} USFTRD_{i,c,k,s} + \sum_{c1} FTRD_{i,c,c1,s} \\ &-FQS_{ics} - \sum_{k} USFTRD_{i,k,c,s} - \sum_{c1} FTRD_{i,c1,c,s} \le FYR_{ics},\ for\ all\ i,\ c,\ s. \end{aligned}$$

where ROW region demand (FDQ), exports to the U.S (USFTRD) and exports to other ROW regions (FTRD) are balanced off against ROW region supply (FDS), imports from the U.S. (USFTRD) and imports from the other ROW regions (FTRD).

Applying the Modeling Framework

The analysis or situations evaluated here may be viewed as a set of “experiments” with the modeling framework. In this case, the experiments involve prospective ENSO conditions.

Specifically, in this analysis two fundamentally different situations will be simulated within the economic framework described above.

- Producers are assumed to be operating without use of any information concerning ENSO phase and thus choose a crop plan (set of crops to be planted in their land base) that represents the most profitable crop mix across a uniform distribution of the full spectrum of the 22 years of events. Hereafter this is called the "Without use of ENSO Phase Information" Scenario.
- Producers are assumed to incorporate information regarding the pending ENSO phase and thus choose a set of crops that is the best performer economically across that individual phase. Thus, crop mixes which are optimized for El Niño events are selected across a distribution of the five El Niño states, as are crop mixes for the other states. Initially, the strengths of each El Niño are assumed to be equally likely. This analysis is called the "With use of ENSO Phase Information" Scenario.

Regional crop yields are uncertain when agricultural planting decisions are made. To portray farmer reaction to this uncertainty, the stochastic sector model includes a yield distribution (Adams *et al.*, 1995). At the time of planting, a number of states of nature (outcomes) concerning future yields are possible and their probability of occurrence is partially explained by the ENSO phase. In this study, regional yield distributions for the crops in the ASM are derived from twenty-two years of historical yield records for various regions of the U.S. These yield data are detrended (to removed effects of technology and other systematic effects) and then sorted by ENSO phase to create yield distributions. The model also incorporates storage of crop production from year to year, allowing some smoothing out of the consequences of each ENSO phase.

In addition to structuring the analysis to vary the response of farmers to ENSO information, a second key component is varied in the model experimentation. In particular. three ENSO phase event probability conditions are evaluated.

- The first represents current conditions with respect to the probability of each phase. Specifically, we assume El Niño phases occur 0.238 of the time, La Niña with a probability of 0.250 and 0.512 for Neutral. Within an El Niño phase, we assume that individual crop yields for five El Niño weather years contained in our data set are each equally likely (i.e, same strength), with a comparable assumption for the four La Niña events and the 13 Neutral yield states.
- The second incorporates the frequency shifts suggested by Timmermann *et al*. Here the El Niño phase occurs with a frequency of 0.339, the La Niña phase 0.351 and the Neutral phase 0.310. Within each of the phases we again assume the cropping yield data states are equally likely.
- The third represents both shifts in event frequency and event strength. The frequency shifts are those from Timmermann *et al.* as computed above. To evaluate event strength shifts, we assume that the stronger El Niño and La Niña events occur with a 10 percent higher frequency. Specifically, if the 1982-3 and 1986-87 El Niños occur each with a 0.20 probability within the set of five El Niño events observed in the data set, above (assuming a uniform distribution across the five observed El Nino's in our data set) we shift those probabilities to 0.25 and reduce the probabilities of the three other El Niño years to 0.167.

Similarly, the two strongest (in terms of yield effects) La Niña states have their probabilities raised to 0.30 from 0.25, while the weaker two La Niñas have their probabilities reduced to 0.20.

Results

Table I contains estimates of aggregate economic welfare before and after the ENSO probability shifts. Table II presents a more disaggregated picture of these economic effects. These economic consequences are evaluated for both situations regarding producer decision-making (ignore or use the ENSO forecasts). The welfare measure is total consumers' plus producers' surplus and foreign surplus. Economic "surplus" is a concept commonly used by applied economists to approximate changes in welfare of individuals or groups. It is a monetary measure which is captured as geometric areas below demand curves and above supply curves. The individual components (consumers, producers) of economic surplus can be compared to see which groups gain and which lose under alternative states of nature.

Three major insights regarding phase shifts and producers' reactions can be drawn from the results of the model experimentation.

- First, the effects of frequency shifts are measured as the difference between the first two rows in Table I (current ENSO frequency vs. the new frequency). The values in parenthesis indicate that there are economic damages arising from the ENSO event frequency shift. Specifically, the welfare loss due to the frequency shift (comparing the first and second rows), ranges from $323 to $414 million. When both frequency and strength shifts are considered (i.e., comparing the first and third rows) the welfare loss increases to the range of $905 to $1,008 million. This is about 5 percent of typical U.S. agricultural net income or about 0.15 percent of total food expenditures in the U.S. The strength shift, if more substantial than the one assumed here, could have substantially larger effects.

- Second, the potential value of ENSO monitoring and of early warning can be assessed by comparing the “with and without ENSO information” columns of Table I. As can be seen from the first row, the use of ENSO forecasts under current ENSO frequency and strength, results in a net welfare gain of approximately $453 million. This value is consistent with the value of information noted in Solow *et al.* Incorporating ENSO information also reduces the negative effects of ENSO phase shifts or increases in strength. Specifically, incorporating ENSO information under the phase shift is approximately $544 million and $556 million under both a phase and intensity shift. The gains to this information are about the same. These gains are greater than under the current ENSO frequency and strength but the gains are in the $100 million range but do not offset the losses due to the ENSO shifts. Thus, the use of ENSO forecasts in producer decision making helps mitigate some of the negative economic effects of the shift.
- Third, the results reported in Table II show that there may be gainers and losers in these outcomes. Specifically, the total welfare loss due to the shift in ENSO frequencies results in domestic producers’ and foreign country welfare losses but gains to domestic consumers. Most of these welfare losses occur in the foreign markets. These differences across groups arise from changes in U.S. and world prices for the traded commodities. For example, there are price declines when phase frequency shifts due to slight increases

in world-wide trade in the commodities evaluated here, which results in losses to producers and exporting countries but gains to consumers.

Concluding Comments

In summary, these findings show extreme events frequency shifts should be of concern. In the ENSO case we confirm Timmermann *et al*.'s speculation that climate change induced shifts in ENSO frequency will have economic consequences. We further find that those consequences involve changes in both the level and variability of agricultural prices and welfare. Prices and welfare fall. The variability of these effects falls as producers anticipate and react to forthcoming El Niño and La Niña events. Timmermann *et al.*'s projected changes can be partly offset by producer reactions to ENSO information, but if ENSO strength also intensifies larger gains can arise by avoiding the climate change that trigger the shifts.

Table I. Aggregate Economic Welfare Comparisons under Shifts in ENSO Frequencies

	Without use of ENSO information	With use of ENSO information	Gain of use of ENSO information
	(millions of U.S. dollars)		
Current probabilities	1,458,947	1,459,400	453
Phase frequency shift	1,458,533 (-414)	1,459,077 (-323)	544
Phase frequency and strength shift	1,457.939 (-1008)	1,458,495 (-905)	556

Note: The value in the ( ) represents the difference with respect to current probabilities due to the ENSO frequency and possibly strength shift.

Table II. Welfare, by Component, With Use of ENSO Information

	Current probabilities	Phase frequency shift	Phase frequency and strength shift
	(millions of U.S. dollars)		
Producers	35,883	35,576 (-307)	35,562 (-321)
Consumers	1,175,699	1,176,290 (591)	1,176,025 (326)
Foreign interests	247,818	247,211 (-607)	246,908 (-910)
Total	1,459,400	1,459,077 (-323)	1,458,495 (-905)

Note: The value in the ( ) represents the difference with respect to current probabilities due to the ENSO frequency and possibly strength shift.

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