CLIMATE RISK MANAGEMENT BASED ON CLIMATE MODES AND INDICES – THE POTENTIAL IN AUSTRALIAN AGRIBUSINESSES

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Abstract

Global and hemispheric climate indicators have proved useful in many countries for characterising intra- and inter-annual variability in climate processes, agricultural output and biomass production. They also form the basis of successful seasonal climate and production prediction systems for the probability distributions of allied parameters such as rainfall or crop yield. Climate risk management via derivative, insurance or bond instruments has only recently incorporated non-local climate parameters such as "teleconnection" indices in payoff functions and overall design. A feasibility study of using the Southern Oscillation Index in weather derivatives for the Australian wheat industry has suggested several such climate-anomaly indicators as suitable vehicles for managing risks of various types, including the hedging of likely errors in seasonal climate forecasting. The potential benefits should accrue if the co-joining of weather/climate risk management and seasonal forecasting is encouraged across many weather-sensitive industries (e.g. agriculture, mining, energy and tourism), if longer-term perspectives of risk across many seasons are adopted and if support is given to suitable trading mechanisms and industry extension programmes.

Keywords

Weather derivatives, SOI, wheat yield, Australian case studies, climate adaptation.

1 Introduction

Probably 70-80% of all Australian businesses have to cater for weather fluctuations, these causing up to 2% variability in gross domestic product; recent studies on the weather sensitivity of industrial supersectors in the United States show a 4% variability, with agriculture, energy, mining and tourism being the worst affected (HARROD ET AL, 2006). Changes in weather typically consist of a "predictable component" (e.g. seasonal cycles) and an "unpredictable component" (e.g. weather "surprises" or "weather noise"). Weather risk management (WRM) involves:

- developing decision and hedging strategies for various time horizons;
- accommodating for the "predictable" component via various types of business-weather models and cycles, be they deterministic, heuristic and/or statistical;
- determining how much weather noise exists (WRM aims to minimise any impacts); and
- estimating distributional characteristics or variability of weather noise over time/space, simulating time series of weather noise at key locations and ensuring the appropriate memory, extremes and transition properties of resultant models.

"Farmers and others are all swimming in the stormy seas of risk, with and without formal climate forecasts" (ANDERSON, 2005) and it is essential to know how important and reliable these forecasts are on an overall and long-term basis. This has of course been true since the advent of agriculture; the interannual variability and required adaptation processes (e.g. crossseasonal storage) are often denoted the "Joseph effect", implying Middle Eastern vintage. For both buyers and sellers of weather insurance and derivatives, the prime importance in current times is usually the forecasting of the probability density functions (pdf) of seasonal accumulations of local or regional weather indices that affect production. The characteristics of the pdf are often related to "climate indicators" now employed for real-time prediction and decision-making in many industries. Climate and production forecasts should always be accompanied by estimates of their errors; risk products can accommodate such "model risks".

Despite experiencing large climate variability and using innovative risk management practices, Australian agriculture has not embraced weather derivatives. This slow uptake can be attributed to illiquidity, basis risks of various types, geographic variability of drought indicators and the perceived high cost of derivative premiums. Such abstinence from weather derivatives is in stark contrast to the mainly enthusiastic response given to seasonal weather/crop forecasting and other prediction methods in agricultural decision-making by farmers, government agencies and research groups throughout Australasia (MANTON, 2006).

Weather markets (and, in future, climate markets) generally consist of:

- end-users (entities such as energy utilities, agribusinesses, transport companies and food/drink manufacturers with real weather risk management needs) who can manage their weather/climate sensitivities by entering into weather contracts at premium prices;
- speculators or risk-takers (participants such as insurance/reinsurance companies, banks and larger producers) who can profit by accepting some weather risks from end-users at premium prices and trade/offset these by both accumulating uncorrelated or negatively correlated risks and dividing up large risks; and
- brokers and other financial intermediaries whose wide knowledge aids transactions.

In the agricultural context, farmers wish to choose a portfolio of parameters (e.g. how much, when, how and where to plant and fertilise/irrigate, which forecasts to select for estimating income and profit at various levels of risk and how much of each risk product to purchase) in order to maximise profits and sustainability, subject to preferred levels of catastrophic and normal risks (see HARDAKER ET AL, 2004 for discussions on coping with risk in agriculture).

Few farm organisations have the chance to use geographical diversification both to optimise decision making and minimise weather risks. Speculators and investors are "farmers of risk", deciding which industry risks to take into a balanced portfolio for maximising sustainable income at a preferred level of risk aversion. Unlike farmers, speculators and investors are unrestricted in geographical basis and can choose major re-insurers to share large-scale risks.

For weather risk, agricultural markets focus on variations in conditions over the growing seasons at the various producers in the country and world. Seasonal weather risks (rather than weekly or monthly as in other weather-sensitive markets) are important and often characterised by the cumulative temperature and rainfall statistics over the growing season. Whilst these parameters are also important in medium- and long-term planning, operation and trading in the energy markets, agricultural production requires further information on soil characteristics and conditions, carry-over of moisture deficits from previous seasons, the time of planting, irrigation and the use of additives such as fertilisers and pesticides (ANDRE ET AL, 2005). Agricultural producers more than energy markets/participants use seasonal climate forecasting (SCF) to aid key decisions and hence may consider risk derivative tools based on seasonal weather – we loosely refer to these as climate derivatives. Although climate is usually understood as long-term weather, in reality there is variability in weather on all time scales, leading to both quasi-periodic ("climate cycles"), trend (e.g. both "climate change" and the influence of changes in observing environment due to urbanisation), seasonal and "weather/turbulence" influences.

For Australian wheat, cotton and sugar, potential yields and sometimes prices show strong associations with climate anomaly indicators (CAIs) such as the Southern Oscillation Index (SOI) and the Antarctic Oscillation Index (AOI), at various lag times and levels of aggregation. The timing/amount of rainfall, the severity of frost and heat stress in crops and livestock, the stream-flows in local and regional catchments and the proliferation of pests and disease are known to be correlated with SOI for many locations (STONE and MEINKE, 2005).

A recent "Land and Water Australia" project explored if the SOI can be used to estimate potential crop yield and price, whether SOI-derivatives are attractive to agribusinesses (in the first instance) and technical issues in such markets. Moderate associations between the SOI and various economic indicators (including farm production) would promote such CAIs as common currencies of climate risk transfer. For the Southern Hemisphere, the utility of SOI-based WRM may increase with the level of risk aggregation that occurs up the production chain, across different states/countries and between industry sectors (BEST, 2007).

Crops such as wheat are grown throughout dryland and irrigated areas from the southern part of Australia through to the sub-tropics, representing a wide variety of climatic and social settings. Climate and crop conditions are usually quite different in the main production regions of Eastern and Western Australia, with eastern production closely tied to tropical Pacific Ocean conditions and western variability more influenced by changes in polar and Indian Ocean states. As climate change and prevalence of weather extremes such as prolonged droughts (together with the need for "short-term adaptation measures" such as SCF) are becoming increasingly recognised, the following research questions emerge:

Q1. Will CAI-derivatives be more useful than other types of weather risk products?
Q2. What benefits may accrue to wheat-industry stakeholders using SOI derivatives?
Q3. How can such products be constructed, priced, evaluated and promoted?
Q4. What synergies exist to users of both seasonal forecasting and climate risk products?
Q5. What are the implications of climate change to WRM in Australasia?

2 Weather derivatives, seasonal forecasting and climate risk management

Farmers in Australia are unusual on the world scene in:

- exporting the majority of their production (e.g. over 70% for wheat, mainly from Western Australia) but yet having relatively little influence on world agricultural prices;
- having considerable exposure to conventional commodity markets (due to issues of international competitiveness, currency risk and the lack of agricultural protectionism);
- operating in an environment of very strong volatility in rainfall, yield and price;
- being conversant in using seasonal forecasting in many forms of decision-making;
- having ready access to government and academic advisors on climate risk management.

The average 15-18% interannual variability in climate conditions (e.g. rainfall) in Australia is greater than that of any other major agricultural country. Drought and extreme temperatures have always formed the backdrop for the survival of farming; almost from the start of large-scale farming, this has stimulated scientific investigations and rational management techniques. For the Australian grain industry, the relationships between wheat yield and climate, soil characteristics and farm management have been the focus of research and development activity over the past 25 years; these techniques and producer experience should aid any fine-tuning of weather/climate risk management tools.

Although Australian Governments at all levels have used drought assistance measures or emergency relief to aid farmers during and after weather/environmental extremes, climate change may alter the long-term sustainability of wheat production. SIETCHIPING (2007) describes the use of broadband-based GIS and expert groups to assist traditional wheat-growing areas to choose optimal routes to sustainable communities. Australia has high quality publicly-available weather data readily accessed at good spatial resolution and low cost. Weather and climate prediction schemes, publicly supported for many decades, are available to all market participants. There is considerable and widely-based experience in agricultural risk management, derivatives (EDWARDS and SIMMONDS, 2004), real options (HERTZLER, 2005), economics and insurance (CHAMBERS and QUIGGIN, 2004), seasonal forecasting of all types (MCINTOSH ET AL, 2006) and the use of education/extension services in agricultural production and commodity trading. Climate risk can be reduced by systematic and informed use of climate analysis into business decisions, from reviewing recent and historical weather records, understanding the impact of CAI-based forecasting tools through to managing climate risk within structural (5-10 years), strategic (1-5 years) and tactical (1-10 days and seasonal) decisions (GEORGE ET AL, 2004).

In advocating both weather insurance and derivative products for use in energy and agriculture, the CERES report (MILLS and LECOMTE, 2006) notes Australia having advantages over other countries:

- weather/climate signals and influences are often very strong (and potentially predictable);
- some mature markets (e.g. electricity) can sustain a variety of innovative products;
- farmers have a strong, well-demonstrated history in general risk management approaches;
- the economy has a high reliance on commodities; their prices have external influences.

The Australian crop insurance market currently only covers hail, fire, frost, lightning, windstorm and malicious acts; yet the demands are for multi-peril crop (predominantly grain), lack of precipitation (dry-land broad-acre, cotton, horticulture and viticulture), frost (viticulture, horticulture and olives), flood (high cost input crops), heat-stress and water-stress (cotton, sorghum, sunflowers, spring grains, livestock), greenhouse-operating, carbon sequestration capacity (forestry), and aquaculture insurance products (SOSENKO, 2007). For grain farmers, the most important variables are yield and price; farmers are able to manage yield risk better than price risk. WYNTER and COOPER (2004) suggest five general strategies are available to wheat producers – cash sales (usually at harvest), a pool system, forward sales and hedging, forward pricing (options and futures) and warehousing (rarely economic).

There is continuing debate on the types and skills of seasonal forecasts for farmers; some believe that predicting plant growth with moderate skill is more valuable than a perfect rainfall forecast. HANSEN ET AL (2006) note that “the predictability of higher-order statistics such as the frequency and persistence of rainfall events, the distribution of dry-spell durations, the timing of season onset and the probabilities of intense rainfall events or temperature extremes” are increasingly important but yet largely unquantified. The emerging focus on “weather within climate” may lead to better spatio-temporal predictability of such quantities, especially for temperature. Global wheat, maize and barley production rates are particularly sensitive to temperature, and appear to have declined over the last three decades, despite increasing carbon dioxide levels and technological improvements (LOBELL AND FIELD, 2007)

Some studies of weather derivatives for Australian crops have emphasised the co-utility of SCF. When used to assess the probability distributions of profits and covering downside risks for a forward-contracted canola crop in Australia, SCF has shown some benefit even during an adverse season such as 2002 (WALLACE and HUDA, 2004), especially if adequate site-specific information aids the associations of SOI phase and on-farm rainfall distributions. STERN and DAWKINS (2004) note that, although there are pockets of Australia in which seasonal forecasts for rainfall outlook have only marginal skill, beneficial risk management using seasonal forecasts <u>together with a partial hedge with weather derivatives</u> requires forecasts only marginally better than climatology. Weather risk tools and the use of currency swaps (to manage price risk) should produce better hedging against drought than waiting to assess the production volume at harvest and selling into an end-of-season pool market.

Climate-related activities in agricultural risk management thus involve the following items:

- the dependence/predictability of planning, production, finance/returns and climate;
- the strength of any associations between production (e.g. yield) and climate indicators;
- the robustness of such links to long-term climate variability and climate change;
- the timescales over which risk management strategies should be considered;
- whether risk products can stabilise income and ensure the survival of market players;
- which new products should be included in the portfolio of products used by a participant;
- any overlap between different instruments (e.g. climate insurance, bonds and derivatives);
- attitudinal changes as international economies adopt new environmental finance measures.

3 Climate modes/indices as currencies for climate risk management

Different CAIs are applicable to various time horizons and include the:

- Southern Oscillation Index (SOI) representing the longitudinal ocean-atmosphere phenomenon ("periodicity" of 3-7 years) with global impacts on climate and production;
- Pacific Decadal Oscillation Index (PDOI) - a decadal oscillation of Pacific Ocean sea surface states that affects Northern Hemisphere climate away from the Atlantic;
- North Atlantic Oscillation Index (NAOI) – a 2-5 year periodicity in non-Pacific Northern Hemisphere pressure patterns that affects production in North America and Europe;
- Antarctic Oscillation Index (AAOI) or similar "polar" measures (SAM or equivalent L, see below) that influence the position of the sub-tropical ridges at decadal timescales;
- Other indices such as Niño 3.4 and the Indian Ocean Dipole Index (IODI) using area-averaged sea-surface temperatures (SST) in key regions of the Pacific/Indian Oceans.

SCF using CAIs has been used in various ways in production forecasting. Various "phases" (e.g. the current state of the SOI and/or PDOI in terms of the index and/or its derivative) can classify the probability distributions of production indicators (e.g. yield, rainfall, temperature) at a future series of intervals (e.g. three months hence). The CAI parameter itself (e.g. monthly SOI), category (e.g. El Niño for SOI < -5) or persistence characteristics (e.g. 3 month running average SOI compared to a threshold) may be used to estimate pdf parameters at a later date. POTGIETER ET AL (2003) have found the spatial variability of Australian wheat yield in "non-normal years" to be well explained by three types of ENSO events. RIMMINGTON and NICHOLLS (1992) suggested that the value of last season's SOI was an important supplement to current SOI in predicting Australian wheat yield, presumably as it is a surrogate for start-of-season soil moisture. Multiple CAIs have been used (e.g. WHITING ET AL, 2003 for predicting Sydney rainfall) to cater for persistent modulation of the SOI by a longer-term behaviour of the PDOI; the SOI and NAOI may similarly yield more regional information on European wheat yields. SYKTUS ET AL (2003) investigated the consequences of different phases of SOI and PDOI equivalent in determining yearly rainfall anomalies for Queensland, using both statistical and GCM techniques. WILLIAMS and STONE (2006) showed that the SOI and the position L of the subtropical ridge co-determine much of the Australian rainfall variability. FREDERIKSEN ET AL (2007) and ENGLAND ET AL (2007) found that the AOI and Southern Annular Mode (SAM) are important indicators of rainfall in southern and western Australia (with links with ENSO via the ocean flows between Indonesia and Northern Australia). TSONIS ET AL (2007) proposed that the collective behaviour of climate indices for 1900-2005 well describes the 20th century shifts in weather regimes (and forecasts future internal variabilities in climate, via coupled GCMs); a necessary and sufficient set of CAIs might then be the SOI, PDOI, AAOI and NAO (or equivalents).

For assessing the utility of CAI products, it is worthwhile to differentiate between:

- those groups using CAIs in their decision-making process – they can then employ CAI-derivatives to hedge their indicator forecasts being wrong or misleading (e.g. model risks);
- those organisations ignoring CAIs for most decision-making - these may still use CAI-derivatives in a portfolio of risk products (e.g. to hedge price-CAI variability);
- traders recognising some signals in CAIs may seek cover from “unpredictable extremes”.

The properties of CAI parameters are important for causality testing, insurance indemnities and the pricing of any derivative products. Furthermore, the statistical characteristics of any predictive models for CAIs should exhibit similar general forms to the historical measurements, if the models are to be trusted. Gumbel-bivariate modelling of SOI event characteristics (e.g. the duration, intensity and peak magnitudes) gives very useful return periods and associated parameters (YUE, 2001). The overall distribution of monthly SOI is bi-modal and may be well approximated (apart from the tails) by a bi-normal function. Various spectral, wavelet and detrended fluctuation analyses of monthly SOI over the available 150 year direct instrumental record show intriguing properties (KIM ET AL, 2005, JIN ET AL, 2005). The overall spectrum has a dominant low-frequency peak (red noise characterised by one or more fractal dimensions) overlain by a very strong peak at 4-5 years and other strong periodicities at 2, 7, and 11 years. Similar properties for other CAIs such as the NAOI have been published (STEPHENSON ET AL, 2000). Multi-fractal analysis of SOI fluctuations suggests two general zones of predictability before and after 8-10 years (AUSLOOS and IVANOVA, 2001). Paleo-proxy information suggests the system has two stable oscillation modes, one with a 3-7 year period and the other a 15 year period.

Stochastic modelling of CAIs for option pricing should preferably use fractional Brownian or Levy-stable formulations (GEMAN 1999, HAMISULTANE 2006) to represent this type of mean-reversion and volatility (not the normal Brownian motion of conventional Black-Scholes option pricing). Climate trend analysis of CAIs should cater for both long- and short-memory effects (COHN and LINS, 2005). Seasonal aggregation of CAIs (e.g. into 6 monthly averages) is likely to produce more normal distributions. The suggested forms for SOI-derivative products (e.g. into six-monthly averages SOI_6 in the analysis below) may then have relatively simple (and even analytic) forms for the payout function and its variance (BANKS, 2002).

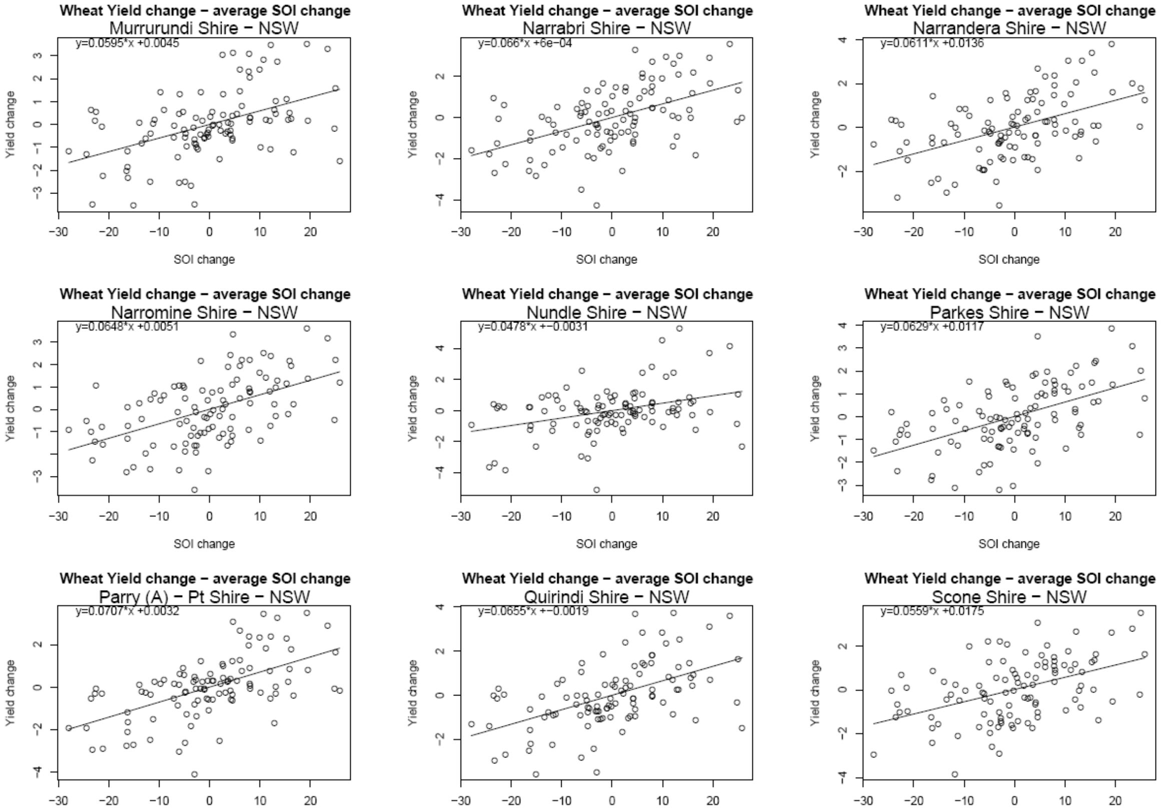
4 CAIs for Australian agriculture – the SOI and wheat industry as a case study

Recent CAI-rainfall studies for Australia (MENEGHINI ET AL, 2006) suggest that the choice of optimal CAI depends on season and region: a better choice than SOI for southern states would be the AOI/L/SAM indices, either singly or in association with the SOI. The SOI appears a better indicator of winter rainfall than SAM for most of New South Wales (except on the Central Coast) and Queensland (except in the tropical north). The emphasis here on SOI is based on the known robustness of climate-SOI links, the much longer historical record, a greater familiarity of farmers with SOI and the limited scope of this LWA project.

Australian wheat yield statistics are no longer routinely gathered by the national agency ABARE, although sufficient historical information is available to test the historical performance (and check on the error distributions) for crop simulation models currently in national use. The deterministic APSIM and semi-empirical Oz-wheat models (POTGIETER ET AL, 2006) include soil properties, initial moisture profile, fertiliser use and technology improvement to predict potential wheat crop yield on a paddock, farm or shire basis.

Estimating the spatio-temporal co-variability between potential wheat yields calculated using Oz-wheat and CAIs (such as the seasonal average of the SOI) assumes few significant model biases with location and over time (e.g. caused by variations in climatic or weather parameters not covered in the modelling). The Oz-wheat model shows wide variations (0-6 kg/ha) in yield between years and across sites. There are many areas where the interannual variability is relatively low and associations of potential yield and SOI are not important. Many sites show high variability and reasonable associations; farms in such shires are better potential users of SOI-derivatives. Oz-wheat predictions of annual yield for the year 2000 (for which high quality, independent information is available) explain 60-80% of the variance over all sites.

Figure 1: Relationships between the annual change in normalised potential crop yield and the annual change in May-October values, SOI_6, for various sets of sites



The normalised yields (i.e. $\underline{V} = (V-V_{av})/ \sigma_v$) show generally similar variability between sites and a fairly stable relationship with changes in SOI_6, itself a normalised variable (Figure 1).

For most sites for 1975–99, simple linear regressions give r^2 of 0.6 – 0.8 for predicted-actual correlations in the simulation model and around 0.25 – 0.45 for model yield and SOI_6. For the 162 available sites, there are 54 with good model performance and strong SOI associations, 36 with good model performance and reasonable SOI associations, 49 with good model performance but poor SOI associations and 6 with poor model performance. Low potential yields are well associated with $SOI_6 < -6$ and very good yields with $SOI_6 > 2$, for shires where potential yield variability is above 20%.

5 Will CAI-derivatives be more useful than other types of weather risk products?

The effectiveness and tradability of CAI-derivatives for agricultural risk management will be principally determined by both the correlation of CAI and financial outputs (such as yield or profit) and the affordability of price-risk returns. The strengths of yield-SOI links described above are reasonably similar to those found for yield and regional weather parameters for many crops (e.g. LOBELL and FIELD, 2007). There is as yet little information on the price-effectiveness of the few WRM or SOI-products offered in the past to judge the relative financial attractions.

MCCARTHY and GRACE (2004) reviewed Australian environmental finance markets and trading schemes in general and note the importance of effectiveness, least cost, administrative simplicity, international compatibility, distributional equity, political feasibility and maximum sector coverage. GOLDFINGER (2004) emphasised the importance of stable segmentation (primary functions, customer and trading venue) and general logistics (commoditisation, intermediation and dematerialisation) for producing sustainable, dynamic risk exchanges. CAI products such as SOI-derivatives can be usefully compared to other weather derivatives and insurances along the following lines:

Global indicator v site-specific index. Rather than dealing with a site-specific index such as Sydney seasonal rainfall, CAI-instruments deal with global parameters (e.g. SOI, NAOI) and so avoid most problems of missing data, measurement error and intra-regional differences. More importantly, they should be more transparent and tradable, since other markets and countries can map their own risks onto a CAI underlying.

Climate anomaly v weather index. Weather derivatives or insurance usually deal with weather parameters at one or more chosen sites; CAI products involve representative modes of behaviour characterised by pressure, wind or temperature differences between widely-separated locations. Weather derivatives depend strongly on having a long and relevant historical record of weather parameters at a number of key locations within a given country. CAIs can usually be constructed for at least 100 years of information (by judicious choice of representative sites) and are potentially applicable to production or weather variables in many countries. CAIs should handle the effects of inter-decadal variability and climate change better than products based on relatively short-term meteorological records; an expanding metropolis with heat-island effects will not represent peri-urban or rural agricultural areas.

Derivative v insurance product. Insurance products are usually based on having a large pool of small, uncorrelated risks rather than wide systemic losses. Moral hazard and adverse selection problems usually result in high transaction costs and more expensive premiums (or require government subsidies or intervention after extreme events). Newer insurance products (catastrophic bonds or options) treat correlated risks and, in agriculture, involve area-yield insurance and exchange-traded area-yield contracts. Insurance products are usually industry-specific with little opportunity for offsetting risks from quite different industry sectors and countries. CAI derivatives do not need farm-level loss adjustment, reducing transaction costs; there is no adverse selection or moral hazard. CAI-derivatives can be used by many industries and may be attractive to global investors for portfolio management as their returns will be poorly correlated with those of traditional financial processes. Market participants from many industry sectors and countries can participate, even developing nations with small historical records of weather or crop yield.

Choice of CAI in a given application. For Australian agriculture, the SOI is initially preferred for its simplicity, the known and robust nature of associations and the availability of reliable SOI-forecasting schemes. For the Northern hemisphere, grain production is usually associated with NAOI or NAOI/SOI. The ultimate choice of CAI will depend on seller/buyer location and application.

Cumulative v timescale index. Agricultural derivatives are usually based on cumulative indices such as growing season degree-days or rainfall. Decision points such as sowing and application of fertiliser are for discrete times and are often assisted by CAI-phase information and forecasts. Although growing season averages of CAI may be statistically easier and meaningful for many applications, risk management of specific events may still be required.

Single v multiple indices. Use of a single index such as SOI or SST may be useful for many applications worldwide as they herald the primary risk of teleconnections. The relationships of production indices with SOI are usually robust, transparent and readily used in determining contract pay-offs and premiums. The intensity of associations of yield and CAI may vary over time and with the anthropogenic forcing of world climate. Although more complex, the use of multiple indices may capture some of this spatial and temporal variability (and hence lead to a more liquid CAI-derivative market) and will also become more popular in SCF.

Interaction with seasonal forecasting**.** Seasonal weather forecasts obviously give useful information in valuing site-specific weather risk products but can involve much expense in updating. CAI products reduce the need to consider forecasts at a wide number of locations and timescales; simple, statistical predictions of CAIs coupled with knowledge of CAI-production links can directly target the pdfs and involve much less arduous computation.

Utility of weather-linked notes or bonds**.** Weather risk bonds give a method of shifting insurance related to non-catastrophic weather events to financial markets; they link the payoff from a derivative to the repayment covenants of a loan or bond, reducing the likelihood of loan default or bankruptcy. Weather-linked bonds based on CAIs may be attractive to many government agencies as an easier way to administer drought relief, and to reinsurance agencies for attracting investors to the weather risk arena.

Thus, in answer to Question 1, weather derivatives in general require no demonstration of loss, making for quicker settlements and a reduction in administration costs and fraud allowances in premiums. There are different and generally simpler legal and taxation issues. Derivatives typically attract many different participants and industry sectors and can be readily incorporated into overall risk management and trading schemes. Fundamentally, weather/climate derivatives are efficient methods of treating volume (or yield) risks.

CAIs should be quite attractive for weather derivatives to a spectrum of stakeholders, both in developed and developing countries. They provide an alternative and more widely marketable set of parameters than potential crop yields; CAI-derivatives should allow some hedge against international price movements caused by climate influences on output in the major producing countries. To some extent, CAI-risk products cover the systemic risk of country-wide climate extremes that can cause problems to micro-insurance schemes (SKEES, 2006); they do not suffer from data issues such as short historical records, expense, and trends from urbanisation near measurement stations or climate change.

Various proxy records for CAIs extend back several centuries and offer a longer-term perspective on the potential impacts of climate change on key industries than available site-specific measurements. CAIs offer more liquidity than risk products based on site-specific parameters, both for the agricultural sectors and for other industries/countries, since various climate modes affect industries in many countries. Focussing on CAIs should also encourage risk management over the more natural timescales of the environment (e.g. 4-7 years for the SOI). These factors should lower premiums, offer more timely settlement (and lower transaction costs) than traditional crop insurance and facilitate climate-linked bonds.

Using CAIs rather than site-specific weather parameters will allow beneficial hedging links to the use of statistical and deterministic schemes for seasonal and multi-year forecasting schemes, especially those operating on a regional or global basis.

6 What benefits may accrue to wheat-industry stakeholders using SOI derivatives?

Agricultural weather/climate risk management for the grain industry involves:

- understanding factors affecting production and eventual profit, at various timescales, to ensure reasonable cash-flow and long-term resilience to unusual/sustained perturbations;
- on-site measurements of production and climatic factors on a seasonal and daily basis;
- reasonable forecasts with errors of forward prices, demand and weather/climate factors;
- appraisals of critical decision points (e.g. what/when/where/how much to sow/harvest);
- knowledge of the susceptibility of farm processes compared to other producers elsewhere;
- considerable understanding of the various risk management products and advice;
- updating of knowledge of the state and predictability of key farm/weather variables;
- appreciation of own risk aversion and those of the main competitors; and
- ability to assimilate the above information in a cohesive, transparent and efficient mode of ongoing decision-making, taking into account both internal and external constraints.

The timescales involved in such decision making are illustrated in Table 1:

Table 1: Agricultural Systems and Climate Variability (STONE and MEINKE 2005)

Decision Type (examples only)	Frequency (years)
Logistics (e.g. scheduling of planting/harvest operations)	Intraseasonal (>0.2)
Tactical crop management (e.g. fertiliser/pesticide use)	Intraseasonal (0.2 – 0.5)
Crop type (e.g. wheat or chickpeas)	Seasonal (0.5 – 1.0)
Crop sequence (e.g. long or short fallows)	Interannual (0.5 – 2.0)
Crop rotations (e.g. winter or summer crops)	Annual/biennial (1 – 2)
Crop industry (e.g. grain or cotton, phase farming)	Decadal (~ 10)
Agricultural industry (e.g. crops or pastures)	Interdecadal (10 – 20)
Landuse (e.g. agriculture or natural systems)	Multidecadal (20 +)
Landuse and adaptation of current systems	Climate change

For this project, interviews with several wheat farmers, insurance and banking groups, traders and market consultants showed that many farmers (at least 10% and especially the larger multi-crop organisations) are keen for offerings of SOI-derivative products, as conventional weather derivatives are unavailable or not felt relevant to farm locations. Insurance products are often of limited use in overall risk management. Insurance companies can experience loss-assessment costs of up to 40% of the premium (as well as other problems such as moral hazard and the need for government intervention or subsidies) and some would find derivative products attractive. Farmers are willing to pay 3-7% of the crop value for farm/crop insurance, 3% of which would be for weather-related non-catastrophic risks. The weather risks of most concern relate to rainfall prior to sowing and during the vegetation stage, heat-stress/cold-stress/frost, waterlogging and availability of streamflow. Many farmers are wary of rainfall risk products because they recognise the high spatial variability in their region. Derivative products need to cover a wide range of weather-related risks to be attractive; the price of premiums on past offerings has discouraged the use of weather derivatives.

There is considerable enthusiasm for SOI-derivatives in many financial traders and risk managers, although company principals may understandably show more reluctance. The limited counterparties for exposures to drought and excess temperatures in the Australian agricultural WRM market emphasises the need for a wider geographical and sector approach. Potential participants from many sectors are still suspicious of the risk management industry; Enron still casts a long shadow. Government assistance should overcome this reluctance.

The climate, risk and technology sensitivities of the various wheat market participants are estimated in a general fashion in Table 2. Farmers within a given region will have a range of risk aversion. Recent surveys (e.g. NGUYEN ET AL, 2006) have shown that the "risk management strategies adopted by farmers were quite similar to those applied by most risk-averse managers". Weather variability is usually ranked as the major source of risk, and soil moisture management of great importance to dryland farmers. Difficulties also arise in sustaining decision-support schemes in small farming communities.

Table 2: General view of the "sensitivities" of wheat market participants in Australia (high H, medium M and low L rankings).

Participant	Climate sensitivity	Risk aversion	Use of seasonal weather forecasting	Utility of weather risk products
Single farmers- all	M-H	M-H	M	M-H
Single farmers- Queensl'd	H	M-H	M-H	H
Single farmers- NSW	H	M-H	M-H	H
Single farmers- Victoria	M	M-H	L-M	M
Single farmers- South A	H	M-H	M	M
Single farmers- Western A	H	M-H	M	H
Multi-farms	M	M	M	M
Stock agents	M	M	L	L-M
Marketers	L-M	L-M	L-M	M
Financial suppliers	L	L-M	L	M
Brokers	L	L	L	M-H
Governments	L	M	L	L-M

The attractiveness of SCF and weather risk products of various types will therefore have a distribution within a set of single farms; any evaluation of their utility should include risk aversion characteristics and the willingness to use seasonal forecasts in decision–making.

Large agribusinesses have a different range of such characteristics. A wide geographical spread of farms may lead to aggregation or diversification of weather risks; simpler weather risk products may suffice and indeed be more effective. Suppliers to agribusinesses are likely to cover a wide variety of farms and crops with aggregated weather risks; demands for various farm inputs should be well correlated with the seasonal average of a CAI. Indeed, even without looking at the associations of commodity prices with CAIs, WOODARD and GARCIA (2006) have shown that most of the aggregated portfolio's weather risk is left in the form of systemic rather than localised form and is better treated by hedging with weather/climate derivatives.

The scope of the recent LWA project allowed only a qualitative response to Question 2. The benefits of risk management using CAI-derivatives with or without adopting CAI forecasting schemes for decision-making should be quantified (for market players with different risk profiles) by using recently-formulated "coherent risk measures" such as the expected shortfall or other spectral risk parameters (DOWD and BLAKE, 2006). SCF effectiveness may be judged by the extra value of information (EVOI – CABRERA ET AL, 2005) represented by the relative change in revenue when using CAI forecasts in such optimisation procedures.

The project concluded that CAIs should be attractive foundations for constructing climate-risk instruments in various commodity markets. The moderate associations of physical or financial yield anomalies with growing season SOI should make SOI-derivative products attractive to eastern Australian wheat farmers, even if they do not use SOI forecasting tools. For agricultural market players, the utility is higher for aggregators of risk such as large agribusinesses and re-insurance organisations. For southern and western Australia, the climate forcings are different and further research is required to identify the optimal, practical mixes of CAIs for both derivative and forecasting schemes. Despite encouraging consensus and positive expectations in wheat farmers and other market participants in Australia for different WRM options, insurance/bank organisations can yet offer few CAI-risk products.

For individual wheat farmers, using derivatives based solely on SOI will be attractive to those with highly-variable potential yields and strong SOI signals in important weather and production parameters and especially useful to those using SOI diagnostics in farm decision processes. For others, further research is necessary to determine the optimal mix of climate indicators and perhaps site-specific parameters to describe well the yield risk. For some farmers, crop-yield derivatives or insurance may be more attractive.

Larger agribusinesses may prefer single index parameters such as the SOI as a surrogate for their weather and climate risks to the alternative of a portfolio of site-indicator underlyings. It may be easier to treat the risks for mixed commodities (e.g. different crops, livestock and alternative income sources such as renewable energy) via climate indicator derivatives rather than multiple yield or weather derivatives. Stakeholders with wider geographic coverage may leverage knowledge from SCF and derivatives based on SOI to treat commodity risks elsewhere in the world. Major agribusinesses, climate risk underwriters, multi-national commodity groups and nations (where considerations focus on all crops and other climate-sensitive industry sectors) may adopt single CAIs in risk products and seasonal forecasting.

7 How can such products be constructed, priced, evaluated and promoted?

For this Question 3, practical implementation issues and the reliability and efficiency of risk management using CAI-derivatives include premium costs, basis limiting, payoff design, pricing techniques, use of more sophisticated prediction techniques for seasonal climate and yield and the implications of climate change. Premium costs of prime concern to farmers may be minimised by the use of multi-year, capped swap or collar contracts, preferably taken over a 3-7 year period for SOI-dominated climates. The geographic variability in Australia may make optimal contract designs quite different for, say, Western Australia and Queensland wheat producers, and for different crops.

Many authors (e.g. TINDALL 2006, JEWSON ET AL 2005 and RICHARDS ET AL 2004 from an agricultural perspective) have reviewed the alternative approaches to pricing weather derivatives; a weather underlying will rarely satisfy the requirements for conventional financial pricing methods to apply. The five general types of pricing methods are:

- "burn" analyses using historical information to evaluate what the insurance risks or derivative payoff functions would be if future weather was very similar to that in the past. For the SOI-derivative based on SOI_6, this will involve a decision on whether to use the last 30-50 years of data (taking a position on climate change), the whole 130-150 year dataset (for statistical reliability) or using only analogue years (e.g. those with the same SOI phase in May). The total premium is likely to depend quite heavily on the choice of data sets but this is a common problem with such "burn" approaches;
- estimation of the statistical distributions of the relevant weather index followed by resampling or simulation schemes. This approach overcomes problems associated with missing data, short data series and choice of data period when using "burn" methods, but requires longer-term proxy records of CAIs and an appreciation of climate trends. For the SOI-derivative based on SOI_6, the full distribution is close to normal and hence specified almost completely by a single mean and variance. For any piecewise linear pay-off function, the pricing can then be performed analytically;
- burn analysis but using the output of stochastic weather generators based on seasonal forecasts and historical information. This may be the easiest way of melding forecasts and their updates as the season progresses and revaluation of contracts is required;
- stochastic differential equation models (e.g. temperature or daily SOI satisfy a "mean-reverting Brownian motion with log-normal jumps and time-varying volatility", not to mention the non-stationarity of mean temperature or regime change due to climate change!). The incomplete nature of the market then requires use of either "risk-neutral" martingale approaches, "equilibrium pricing models" to incorporate the market price of risk or models that implicitedly include a risk premium for the non-traded asset;
- modified Black-Scholes techniques, e.g. accumulated weather indices have almost-normal distributions and conventional pricing techniques may be appropriate.

Any mis-specification of the weather/climate processes can lead to an overpricing of derivatives; in some situations, the risk premium can be a significant part of the derivative price; taking the market price of risk to be small could lead to significant pricing errors. If time aggregation over a season is used, the importance of "process dynamics" may be reduced. Nevertheless, for CAI products, simulation techniques are likely to be required for the variety of non-linear pay-off functions to be employed. As CAIs may also be involved in decision-making and portfolio optimisation, conventional option pricing models may have to include model risk and techniques that have proved valuable in other incomplete markets.

In this feasibility study, the associations of SOI and potential winter crop yield for wheat in Eastern Australia suggest an initial payoff function for pricing and outcome analysis:

- contract period of 1 May – 31 October;

- measurement variable as the average SOI index SOI_6 (as defined by the Australian Bureau of Meteorology) over that period (i.e. an Asian option);
- a pay-off function of the collar form

$$F(SOI_6) = \begin{cases} m & SOI_6 < -12 \\ D_1(SOI_6 + 6) & -12 \leq SOI_6 < -6 \\ 0 & -6 \leq SOI_6 < 4 \\ D_2(SOI_6 - 4) & 4 \leq SOI_6 < 8 \\ -M & SOI_6 \geq 8 \end{cases}$$

  where m is the capped payout ($6D_1$) to the farmer for severe drought (characterised by SOI_6 below -12) and – M is the capped payment ($-4D_2$) from the farmer in the event of large positive SOI_6 (and hopefully a bumper crop). The ratio of D_1/D_2 may vary between different sites and may well be represented by the site crop yield volatility.
- premium to be defined by a transparent pricing process, probably based on the sum of expected pay-off, risk premium and transaction costs;
- measurement responsibility in the hands of the World Meteorological Organisation;
- settlement agency and methodology possibly to extend over several seasons.

Historical records of SOI_6 show that, for the years 1876-2005, there have been 10 years with $SOI_6 < -12$, 30 years with $SOI_6 < -6$ and 26 years with $SOI_6 > 6$. Furthermore, low values of SOI_6 are fairly well predicted by the SOI phase in May (two of the five phases are strongly linked with positive SOI_6, one phase accounts for most cases of $SOI_6 < -6$). The contract pay-offs themselves may be usefully estimated at contract initiation from SOI phase information.

Table 3 gives the mean and standard deviation of SOI_6 corresponding to the concurrent potential yield records, the earliest set of SOI records (1876-1909) and two identified warm and one cold multi-decadal epochs of the 20th century. Whilst the volatility of the SOI_6 is quite steady, there are significant shifts in the means for the various periods. The collar payoff given above has been used with $D_1=50$ and $D_2=25$ arbitrary units. Whilst the choice of data set leads to considerable variability in mean pay-off, the statistics for the volatility of F are reasonably stationary. The average premium (calculated by adding on 20% of the standard deviation of the pay-off) and farmer's net profit (pay-off minus premium) are shown for the various periods; with the premiums being varied using hindsight (an artificial device), the farmer has sacrificed a small premium in all years for supporting pay-outs in poor years and small payments in good years.

Table 3: SOI_6, pay-off function, premium and net profit for various epochs.

Epoch	Mean SOI_6	SD (SOI_6)	Mean F	SD(F)	Premium	Farmer net
All (1901-2005)	-0.65	8.01	20.5	115	43.5	-23.0
Warm 1 (1910-47)	-0.04	8.08	22.7	105	43.8	-21.0
Cold (1948-77)	1.34	8.36	10.4	115	33.5	-23.0
Warm 2 (1978-2005)	-2.12	7.68	52.7	128	78.3	-25.0
1876-1909	-0.05	8.56	22.8	122	47.3	-24.5

The above technical issues pale into insignificance compared to those concerning the establishment of exchange sectors willing to deal in CAI-risk products. Many sectors that have traditionally used weather risk products (Table 4, University of Houston, 2005) will have risks correlated with CAIs and may offer offsets of risks for providers of CAI-derivatives. These sectors can be screened on a national and world-wide basis for the spreading of risks, if CAIs are used in the portfolios of weather/climate risk products.

Table 4: Buyers of weather risk products

Sector	Risks
Agriculture	Crop yield, handling, storage, fertiliser use, pests
Aid agencies	Disaster and economic relief (e.g. weather/climate bonds)
Construction	Delays, incentive/disincentive clauses
Energy	Reduced or excessive demand, energy storage and generation
Entertainment	Postponements, reduced attendance
Fisheries	Reduced supply, delays
Governments	Budget overruns, disaster relief, interest rates
Insurance	Increased claims, premium diversification
Manufacturing	Reduced demand, increased raw material costs
Offshore projects	Storm frequency, severity and losses of various types
Retailing	Reduced demand of weather-sensitive products
Transportation	Budget overruns, delays
Water resources	Supply, storage and demand, use of expensive alternatives

Table 5 lists possible offsetting measures for hedging SOI-derivatives; the viability of these alternatives will depend on the size, geographic spread and risk appetite of the various market players.

Table 5: Potential offsets to SOI risk for Australian wheat market players.

SOI_6	Australian farmer outcome?	Potential offsets
Large negative	Low rainfall/yields in Eastern states; poor moisture availability; heat stress or frost damage.	High crop production in North America. Increased tourism in Australia. Fewer construction delays in Australia
Around zero	More average weather conditions and crop revenues. Some storm damage at harvest times.	Storm damage to power networks in Australia
Large positive	High rainfall and crop yields (unless pests/disease or waterlogging occur)	Low crop production in North America. Interruptions in tourism and construction in Australia. Improved performance for hydropower and water resources in Australia

Although there is no climate trading market as yet, there is a rising expectation of greater interactions between the markets for climate/weather products, energy (e.g. electricity, gas, wind), fuels (e.g. oil and biofuels such as ethanol from wheat and other crops –CASSMAN 2007), various agricultural commodities and the greater variety of reinsurance products now brought about by more expensive climate extremes.

This may lead to much greater liquidity, if the products are proven reliable and efficient. Reliability in this context is viewed as the ability of the CAI-derivative to provide a consistent measure of risk reduction over decadal timescales, with little change in geographic bias or association with yield, for a given site. Efficiency could be measured by the degree of risk reduction garnered by using the CAI, based on spectral risk or similar measures with specification of the preferred risk aversion profile.

8 What synergies exist to users of seasonal forecasting and climate risk products?

Forecasting and stochastic simulation models are increasingly important in Australian agriculture for various reasons centred on the high volatility in climate:

- precision agriculture involves the combination of scientific models and practical experience in producing multiple crops for world-wide markets that operate in an uncertain and changing economic environment;
- risk assessment requires the coupling of weather/climate simulations and production models (both of which are complex, non-linear devices);
- climate change complicates the use of historical data for pricing weather derivatives.
- evaluating hedging effectiveness for farm operations includes sensitivity analyses of alternative climatic outcomes and management strategies for various risk propensities;
- "ensemble" weather/climate models can now give a range of forward climate paths – the mean path is likely to yield the "fair price" of any option whilst the variance in forecasts will be involved in determining the risk premium for the contract;
- JEWSON ET AL (2005) review the use of meteorological forecasts in derivative pricing; they note the considerable difficulties in combining weather and seasonal forecasts and outline the simpler use of seasonal forecasts to select historical climate data used for contract pricing;
- conventional derivative pricing methods usually assume a linear yield-index relationship and an absence of mean reversion and sudden jumps in the underlying. Inclusion of non-linearity and true statistical characteristics of weather variables/indices is necessary for Australian conditions and is likely to require stochastic simulation techniques;

The downscaling of probabilistic seasonal forecasts to different time and spatial scales (e.g. daily parameters at several farm sites) may be usefully achieved using stochastic weather generators (WILKS, 2005); ensembles of such synthetic weather paths can then be used with crop simulation models to forecast yield distributions (and even in the absence of reliable seasonal forecasts, see LAWLESS and SEMENOV 2006). Seasonal forecasting in Australia is more often downscaled to shire or farm level using SOI and site history, encouraging fuller knowledge of basis risks.

These CAI associations and lags provide opportunities not only in various WRM/SCF processes in hedging climatic influences in volume and price risk, but also in providing reality checks on the utility and characteristics of deterministic models for global weather and climate. Decisions in agricultural production may be required at times when model predictability is low; it is then most beneficial to seek some financial offsetting of the risks of using such forecasts by purchasing or optioning weather-index insurance and/or derivatives. Widespread use of CAIs (especially the SOI) for decision-support within the Australian grain industries will facilitate both using CAI-derivatives as natural hedges against unexpected behaviour in the underlying index and the development of better seasonal prediction schemes (Question 4).

9 What are the potential implications of climate change to WRM in Australasia?

Both the long-term variability in climate and recent anthropogenic climate changes (Question 5) pose various challenges and opportunities to climate risk management. Recent warming, severe droughts and current regional climate modelling for Australasia out to the year 2100 all suggest agriculture having to face major challenges to its existence and sustainability in many areas. Short-term adaptation techniques for the grain industry, for example, are likely to include a deeper response to climate sensitivities and carbon pricing of agricultural inputs and processes and the rapid adoption of innovative risk transfer.

For WRM, the pricing of instruments may depend heavily on the choice of epoch for historical information or simulation schemes and/or on the confidence in near-term climate prediction methodologies. Increasing awareness of climate change issues in the general commercial and industrial communities should aid the uptake of CAI-derivatives as an adaptation adjunct to the rapidly-developing environmental trading markets (e.g. for carbon, combustion pollutants and water). The introduction of climate derivatives should encourage more realistic timescales in farmer risk management (e.g. pay-off schemes over the natural “time period” of climate modes) and improved political and/or social responses. Both moderate-risk and extreme events need careful evaluation and better estimates made of the likely return periods (especially with such limited historical observations). The past suddenness of climate transitions (e.g. 1975-7) and the unusual nature of the past 30 years should encourage caution (KRAVTSOV and TSONIS, 2007). This obvious non-stationarity of statistical properties clouds both the use of historical simulation and traditional stochastic models in pricing methodologies and the rational selection of past analogues in climate.

Abrupt changes such as regime shifts of interannual climate modes will challenge evaluation of costs and the existence of optimisation procedures for climate policy analysis. Direct measurements of the SOI are only available from 1850 onwards. Proxy records back to 1520 (GERGIS and FOWLER, 2006) show that the 20th century has experienced a preponderance of extreme negative SOI events. Ice-core records (THOMPSON ET AL, 2006) suggest ENSO influences being important for at least 2000 years; abrupt climate changes at low-latitude, high-elevation sites similar to the past 35 years last occurred 5200 years ago and were then coincident with structural changes in several civilisations. Recent climate modelling of various pedigrees seems to confirm that such a bias is likely to continue well into the 21st century (CABOS NARVAEZ ET AL 2006, POWER ET AL 2006). Equally of concern are recent studies showing an influence on polar climate (and the explanatory power of SAM) from global warming and ozone losses in the Antarctic vortex (CAI, 2006). Various climate changes may influence the stability, interaction and consequences of climate modes and necessitate adaptation processes for more abrupt transitions than experienced recently.

10 Summary and reflections on global potential?

Many ventures in weather derivatives have failed because of difficulties in finding counterparties, complexities in product structure (mainly to avoid basis risk) and the inability to attract the full range of stakeholders in various industry sectors and countries. Agricultural weather risk management has dwelt on site- or area-specific temperature and rainfall derivative and insurance products with little co-ordination with seasonal forecasting methods and decision-making processes.

Climate teleconnections provide a rich tapestry to interweave seasonal forecasting and climate risk management; CAIs can be used both to capture much of the variability in weather and production parameters and to form the basis of successful forecasting schemes readily adopted by individual stakeholders such as farmers. CAIs are therefore attractive in forming underlyings for use in weather and climate derivatives and avoid most problems encountered when using only site data. CAI data and predictions are publicly available, aiding liquidity and avoiding moral hazard; proxy data for the SOI and NAOI extend the history back to at least the sixteenth century and may assist in detecting climate trends and correlations.

Current research into multi-model ensemble global climate forecasting, the connectivity of climate modes and the dependence of climate extremes on CAI interactions should aid the ongoing and full estimation of the probability density functions that are the basis of maintaining a portfolio of weather derivatives.

Derivatives, insurance and bond products based on CAIs offer (to a wide range of counterparties) the same set of indices for use in multi-dimensional payoff functions and in hedging the inevitable errors involved in seasonal climate and production forecasting.

Variances in crop production and returns in many countries have been shown to be associated with CAI variability, although the strengths do vary spatially and over multi-decadal periods. As the scale of stakeholder coverage increases to include larger agribusinesses, finance providers and government organisations, aggregation of risks should result in single-index climate derivatives and bonds being more attractive; this should facilitate international trading whilst seasonal forecasting on a worldwide basis can use one or more CAIs.

For many Southern Hemisphere industries, derivative contract structures can be usefully based on seasonal averages of the SOI in, for example, a collar payoff function, preferably over a multi-season timescale corresponding to the dominant periodicity in the SOI (say 3-5 years). Such quasi-linear structures for the seasonal-averaged CAI lead to near-normal probability distributions for the underlying climate index, thus facilitating modelling, pricing and forecasting methodologies.

For the example of the Australian wheat industry, the use of potential crop yields (calculated by semi-empirical or deterministic simulation schemes) avoids some of the problems of asymmetric information and facilitates the aggregation of production estimates. At the shire level, potential yield is strongly associated with six-month SOI for Queensland and New South Wales but other forms of CAI may be required in the southern states.

SOI alone is useful for assessing national and international production and as a minor indicator of agricultural commodity price variability. Similar results can be expected for other crops and countries, perhaps with different CAI sets (but with the SOI being a common member). SOI-derivatives can form a useful addition to current risk management schemes, especially for those stakeholders already using the SOI as a decision-making aid. Indeed, hedging model errors allows a more rational allocation of resources to crop forecasting and the evaluation of financial returns at harvesting.

Climate risk management for agribusinesses, climate risk underwriters, multi-national commodity groups and nations (where considerations focus on all crops and other climate-sensitive industry sectors) may initially adopt single CAIs for risk products and seasonal forecasting. CAI derivatives can service weakly-linked sectors such as agriculture and energy production and form the basis for aid to poorer countries with high impacts of climate variability (e.g. SOI-linked bonds).

Climate indicator risk products are likely to be useful in countries with strong SOI influences on their economies, especially those with short or poorer quality weather records or those requiring rapid monetary aid for drought relief. Climate derivatives may also be useful in the forthcoming carbon risk markets (e.g. variability in net primary production and carbon uptake can be partially explained by climate indicators).

Many climate indicators have similar spectral, scaling and persistence properties; this facilitates forecasting and risk management. Predictive models that reproduce these are to be preferred whilst the natural time horizons and scope for climate risk management may be evident from the strength of any associations of climate indicator and production variables.

Future research can focus on the robustness, non-stationarity and non-linearity of the relationships of yield and climate indicators (as these influence the utility and design of any derivatives), the optimal form of CAI-derivatives for various commodities, the treatment of portfolios of CAI-products, the fuller use of seasonal forecast errors in climate risk management, the matching of instrument choice with farm characteristics and stakeholder risk profiles and the use of multiple indicators, especially for price signals and in derivative design for locations with lower climate variability. Climate and weather derivatives of various forms will become more readily adopted if a multi-sector approach is encouraged by bringing together stakeholders from the agriculture, energy, tourism, water supply, construction, finance and environmental areas – an initial objective in Australia might be to rationalise the development of general environmental markets.

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