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Perspective

Funding climate adaptation strategies with climate derivatives

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ABSTRACT

Climate adaptation requires large capital investments that could be provided not only by traditional sources like governments and banks, but also by derivatives markets. Such markets would allow two parties with different tolerances and expectations about climate risks to transact for their mutual benefit and, in so doing, finance climate adaptation. Here we calculate the price of a derivative called a European put option, based on future sea surface temperature (SST) in Tasmania, Australia, with an 18 °C strike threshold. This price represents a quantifiable indicator of climate risk, and forms the basis for aquaculture industries exposed to the risk of higher SST to finance adaptation strategies through the sale of derivative contracts. Such contracts provide a real incentive to parties with different climate outlooks, or risk exposure to take a market assessment of climate change.

Introduction

Adapting to climate change requires large amounts of capital investment, which is most often sought from central governments (Aakre et al., 2010), but could also be obtained from capital markets. The global derivatives market, with a value estimated to be greater than 100 trillion USD (Hull, 2009; Anonymous, 2011), is an untapped source of capital for adaptation efforts. Derivatives offer a financial incentive to parties with differing risk exposure, or opinions of future climate outcomes, to transact. Using downscaled climate model projections we calculated prices on which such transactions could be based.

Climate derivatives have potentially widespread application for funding adaptation efforts including in tourism, energy generation and agriculture (Thornes, 2003). Aquaculture represents an important source of food production in the future, but has concomitant economic and financial risks (Godfray et al., 2010). Recent climate forecasts and concern about the susceptibility of the Tasmanian salmon aquaculture industry to warming ocean temperatures motivated us to look for solutions to the climate challenges they face. The industry, worth over 500 M AUD in 2011–12 (DPIPWE, 2013), is considered vulnerable (Battaglene et al., 2008) because salmon are currently grown in coastal waters that in some years exceed a thermal limit of about 18 °C, with observed coastal warming in the region (Hill et al., 2008; Lough and Hobday, 2011)

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predicted to continue (Grose et al., 2010; Hobday and Lough, 2011). Efforts are currently underway to reduce the risk of warming coastal waters by several aquaculture companies; here we suggest that selling climate derivatives to investors could provide additional capital for these and extended efforts.

Climate derivatives

A derivative is a financial product that derives its value from an underlying asset or index such as a share price. It is a contract between two parties, where one (the writer) promises to make a financial commitment to another (the purchaser or contract owner) if pre-defined conditions associated with the underlying asset eventuate. In return for this promise and the financial risk it entails, the writer receives an up-front payment.

In general, financial derivatives are used for three reasons: to hedge against unwanted financial risk; to speculate in the hope of financial gain; or to benefit from asymmetry in information or circumstances via arbitrage. Derivatives are commonly used as a market-based instrument to transfer risk from one party that is exposed to risk, to another that is considered able or willing to bear it.

There are several types of derivatives; one of the most commonly used, called an option, is a contract that gives the owner the right, but not the obligation, to exercise the contract at a specific condition of the underlying index, called the 'strike' by a deadline called the 'maturity date'. Options come in different types. A 'call' option gives the contract owner a pay-off if the underlying index is above the strike by the maturity date, while a 'put' option gives the contract owner a pay-off if the underlying index is below the strike by the maturity date.

Options are further distinguished by the conditions under which they can be exercised. A "European" option can only be exercised at the maturity date, while an "American" option can be exercised prior to the maturity date. Thus, a European put option will generate a pay-out to the owner only if the underlying index is below the strike at the maturity date, while an American call option could, if the owner so decided, pay-off if the underlying index is above the strike at any time before the maturity date.

Here we provide an example of a European put option, based on forecasts of sea surface temperature (SST) that can be exercised at a maturity date to give a $100 pay-out for each degree the summer SST deviates *below* 18 °C. Crucially, aquaculture companies who wish to further adapt to climate change would use the up-front payment to invest in efforts such as selective breeding to develop more thermally tolerant fish, or relocation of production facilities to cooler, open-ocean offshore operations (Hobday and Poloczanska, 2008). If ocean conditions at maturity remained *below* the 18 °C threshold the contracted aquaculture company would be obliged to make a pay-out to the contract owner or investor, but would be compensated by the upside benefit of not incurring the risks and costs associated with a higher SST. By contrast, if summer temperatures rise *above* the 18 °C threshold, a contracted aquaculture company would not be obliged to make a pay-out. Instead, it would benefit from the investment made in adapting to higher water temperatures.

Pricing climate derivatives

The price at which a derivative is traded relies on several components: an underlying index or asset price forecast, the pay-out and exercise conditions, the strike and the lifetime or length to maturity.

Underlying index

Models that capture the processes governing the dynamics of the underlying index could provide reliable probabilistic forecasts, and thus accurate derivative prices (Caballero et al., 2002; Little et al., 2014). Climate models simulate the physical processes that influence atmospheric and oceanographic quantities such as temperature, pressure and precipitation at large spatial and temporal scales (Stock et al., 2011), and have been used to project future climates and inform climate adaptation planning and risk assessment (Stock et al., 2011; Holz et al., 2010; Tabor and Williams, 2010). At short time and small spatial scales, models disagree and their predictive power is much debated (Stott et al., 2010; Maslin and Austin, 2012; Whetton et al., 2012). Technically, climate model forecasts could be used to price a derivative, but their use is complicated for two reasons. First, general circulation models (GCMs) used to project future climate scenarios have coarse spatial resolution (e.g. 2×2 degrees; Stock et al., 2011) with forecasts for adaptation plans typically needed at a finer regional scale (Jewson et al., 2005). Most aquaculture sites in Tasmania, for example, occur in regions within a radius of about 10 km, and there is great habitat diversity among sites. Second, climate risk modelling and derivative pricing require probabilistic forecasts (Whetton et al., 2012; Dessai and Hulme, 2004), such as those from ocean and weather forecasting, (e.g. Oke et al., 2008) while many GCMs are deterministic. Down-scaling (Pielke and Wilby, 2012), employing multiple models (Hobday and Lough, 2011) and estimating uncertainty address these issues and provide a basis for climate risk modelling and derivative pricing.

The underlying index for this example was defined as the average annual summer (Jan., Feb., March) SST in the D'Entrecasteaux Channel of south east Tasmania (43.05°S, 147.18°E). Model forecasts for SST were obtained from the Climate Futures for Tasmania (Grose et al., 2010) based on an ensemble of 12 GCM forecasts consisting of two IPCC Emission scenarios (A2, B1) and six different GCMs (CSIRO-Mk3.5, GFDL-CM2.0, GFDL-CM2.1, ECHAM5/MPI-OM, MIROC3.2, UKMO-HadCM3). The data from these models were dynamically downscaled to the region using the Conformal Cubic Atmospheric Model for the period from 2010 to 2050 (CCAM; Corney et al., 2010).

Probabilities associated with SST projections for the period 2010 to 2050 were generated first by fitting three autoregressive moving average (ARMA) models of order 0–2 to each of the 12 GCM forecasts; secondly for each of the GCM forecasts, one model was selected from the three fitted ARMA models based on the lowest Akaike Information Criterion (AIC) value (Table 1). Then, for each of the 12 selected ARMA models, 100 multivariate normal samples were then taken of the estimated parameter coefficients (intercept, trend, autoregressive, and moving average), and used to derive an ARMA simulation of SST from 2010 to 2050. This gave an ensemble of 1,200 downscaled time series of SST.

We used the 4-year average summer SST as the underlying index for the derivative prices calculated. A 4-year average SST was used to better reflect the risk of a general temperature trend crossing the threshold, rather than the influence of interannual variability.

Price calculation

Prices were calculated by discretizing the real-valued underlying index $x_{k,t}$ from simulation k of the ensemble in year t, into one of $s = 1 \cdots 1000$ discrete bins, as $a_{k,t,s} = 1$, such that $\tilde{x}_{s_t} \leqslant x_{k,t} < \tilde{x}_{(s+1)_t}$, with $\tilde{x}_{s_t}$ and $\tilde{x}_{(s+1)_t}$ representing the underlying index at time t, of two discrete contiguous bins s, and $s + 1$.

The derivative price is the payment the writer of the contract requires for incurring the risk of a pay-out, which depends both on the probability of the pay-out occurring, and the size of the pay-out should it eventuate. We calculated the probability of pay-out from the ensemble of 1200 time series trajectories. The pay-out size was defined as a function based on the underlying index relative to the strike,

$$I_{s,t} = \begin{cases} C|\tilde{x}_{s_p} - \tilde{x}_{s_t}| & \text{if } \tilde{x}_{s_t} < \tilde{x}_{s_p} \\ 0 & \text{if } \tilde{x}_{s_t} \geqslant \tilde{x}_{s_p} \end{cases}$$

where C is a scaled pay-out parameter, $\tilde{x}_{s_p}$ is the discretized value for the bin representing the strike and, $\tilde{x}_{s_t}$ is the discretized value of the underlying index for bin s at time t. (For call options the inequality conditions in the pay-out function are reversed.) This pay-out function implies that pay-out increases with the deviation of the underlying index from the strike.

Prices were calculated in two steps. First, the probability of the discretized underlying index in bin s at time t occurring i.e. $p(\tilde{x}_{s_t})$ was determined as:

$$p(\tilde{x}_{s_t}) = \frac{1}{n_k}\sum_k a_{k,t,s}$$

where n_k is the number of simulations in the ensemble (i.e. 1200).

The second step involved calculating the present value of the expected pay-out at maturity date $t = T$, discounted using a backward induction process to time $t = 0$ recurrently as,

$$E[I_{T-1,s'_{t-1}}] = e^{-\delta}\sum_{s_T} I_{T,s_T}\, p(s_T|s'_{T-1})$$

where $E[I_{t,s_t}]$ denotes the expected pay-off for discrete bin s_t at time t, $p(s_{t+1}|s'_t)$ is the conditional probability that the index value will be in bin s at time $t+1$, given it was in bin s' at time t, and is calculated as $p(s_{t+1}|s'_t) = p(s_{t+1}, s'_t)/p(s'_t)$, where $p(s_{t+1}, s'_t)$ is the probability of the index being in bin s'_t at time t, and bin s_{t+1} at time $t+1$. δ is the discount rate.

Table 1
Fitted ARMA models for 12 downscaled global climate model (GCM) trajectories of sea surface temperature to the year 2050 showing autoregressive and moving average parameter estimates (±S.E. in parentheses): AR(1) auto regressive coefficient order 1, AR(2) order 2, MA(1) moving average coefficient order 1, MA(2) order 2, intercept and trend, and model variance (Var.).

	GCM	AR(1) coeff.	AR(2) coeff.	MA(1) coeff.	MA(2) coeff.	Intercept	Trend	Var.
1	UKMO-Had CM3 B1	0.33 (0.15)	–	–	–	17.93 (0.35)	−0.01 (0.015)	0.55
2	UKMO-Had CM3 A2	–	–	–	–	17.34 (0.21)	0.05 (0.009)	0.44
3	MIROC3.2 B1	–	–	–	–	17.64 (0.25)	0.0018 (0.01)	0.60
4	MIROC3.2 A2	−0.02 (0.15)	0.50 (0.15)	0.00 (0.10)	−1.00 (0.09)	17.01 (0.13)	0.04 (0.006)	0.66
5	GFDL-CM2.1 B1	–	–	–	–	17.34 (0.17)	0.02 (0.007)	0.29
6	GFDL-CM2.1 A2	0.52 (0.123)	−0.77 (0.142)	−0.96 (0.12)	1.00 (0.12)	17.41 (0.13)	0.02 (0.005)	0.22
7	GFDL-CM2.0 B1	−0.27 (0.15)	–	–	–	16.73 (0.12)	0.01 (0.005)	0.23
8	GFDL-CM2.0 A2	−0.61 (0.18)	−0.49 (0.15)	0.73 (0.09)	1.00 (0.13)	16.83 (0.19)	0.02 (0.008)	0.21
9	ECHAM 5/MPI-OM B1	–	–	–	–	17.45 (0.40)	0.02 (0.02)	1.54
10	ECHAM 5/MPI-OM A2	–	–	–	–	17.97 (0.41)	0.01 (0.02)	1.62
11	CSIRO Mk3.5 B1	–	–	–	–	16.90 (0.17)	0.03 (0.01)	0.27
12	CSIRO Mk3.5 A2	0.69 (0.14)	−1.00 (0.07)	–	–	16.74 (0.05)	0.02 (0.002)	0.14

The price of a European type option contract, which can only be exercised at maturity, is independent of the underlying index state prior to maturity, and calculated simply as the expected pay-off at time T. An American style option contract, which can be exercised at any point prior to the maturity date T, is path dependent, and requires a decision at each time t on whether to exercise the contract and invoke a pay-out or wait. The expected pay-off at each time step t, $E[I_{t,s_t}]$, captures this decision based on the objective of maximising pay-out, by choosing the greater pay-out expected between exercising the contract at the time I_{t,s_t} or waiting $e^{-\delta}I_{t+1,s_{t+1}}$. Namely,

$$\mathrm{E}[I_{t,s_t}] = \max(I_{t,s_t}, e^{-\delta}E[I_{t+1,s_{t+1}}])$$

(For generality, a European option would not have this choice, and would just be $\mathrm{E}[I_{t,s_t}] = \max(0, e^{-\delta}E[I_{t+1,s'_{t+1}}])$.)

The price, thus is defined as $\mathrm{E}[I_{t=0,s_{t=0}}]$. Where the initial state at time $t = 0$ is uncertain, the price is determined as the expected outcome across all possible initial states,

$$\mathrm{E}[I_{t=0}] = \sum_{s_{t=0}} p(s_{t=0})\mathrm{E}[I_{t=0,s_{t=0}}]$$

Conditions

European put option prices were calculated for a $C = \$100$ pay-out for each degree deviation from a strike level of 18 °C, over a maturity period, T, of 10 and 20 years, discounted to present value at a rate of 7%. In addition, for comparison, we also show the associated risk in the absence of warming SST by calculating European put option prices using an ensemble derived from ARMA simulations with the trend parameter set to zero.

Results

The downscaled climate model forecasts (from Corney et al., 2010) were highly variable between models (blue lines, Fig. 1). All except one of the ARMA models that were fitted showed increasing temperature trends (Table 1). These trends were also indicated in the mean ARMA simulated trajectory across the different GCMs (black lines, Fig. 1), as was the degree of annual variability in temperature (grey areas, Fig. 1).

The prices, which were defined as the discounted expected pay-out, considered both the future range of summer SSTs and the probability of occurrence. Put option prices based on these data ranged between \$45.85 and \$61.10 depending on maturity date (Fig. 2). We also calculated the put option prices of a contract based on forecasts that omitted the estimated warming trend (Table 1). These prices were higher (\$78.99 and \$79.02), implying that without a warming trend, lower SSTs and a higher likelihood of a pay-out would be expected.

Discussion

A climate derivative contract in the form of a European put option provides an opportunity to raise capital proactively for investing in a climate adaptation strategy. For each contract sold, an aquaculture company could raise capital of \$45.85. Thus to raise 1 million dollars, the company could issue or write 21,810 contracts. If the average summer SST were to remain below the 18 °C at the time of maturity, the aquaculture company would be obliged to pay-out to the contract owners a total \$2,181,025 for each degree that the average summer SST was below the 18 °C strike level. If average annual SST were to rise above 18 °C at maturity, then it would not be obliged to make a pay-out, but enjoy the benefit of the up-front contract payment to fund adaptation efforts.

An alternative reactive, rather than proactive, risk management strategy would be to use an American call option, which would pay-out if the average summer SST were to rise above the strike level during the lifetime of the contract. In this case, the company would instead purchase a contract, like an insurance policy, with the intention of receiving compensation if the summer SST exceeded the 18 °C strike level. The company would thus need to choose a specific strategy with an eye also to considering other non-climate risks relating to economic, political and demographic trends that might be expected over the timeframe.

From the perspective of the counterparty or investor, climate derivatives offer the opportunity to hedge against potential economic losses, or take advantage of different climate outlooks or risk tolerances, and align incentives to provide a mutual benefit. In the specific case of Tasmanian aquaculture, possible counter-parties to the aquaculture industry for a European put option would be those who would experience economic losses if warming did *not* occur. For instance, viticultural investment in warm climate wine grapes, as grown in lower latitudes of Australia, offers significant economic opportunities in Tasmania under a warming climate (Holz et al., 2010), but also poses economic risks if warming does not occur. Parties taking on such an initiative may wish to offset this risk by purchasing European put option contracts from the aquaculture industry.

Additionally, parties who do not expect higher ocean temperatures to eventuate also have a strong financial incentive to enter these transactions. Our results show that a party that does not expect SST to increase above the strike threshold would expect a \$79.02 pay-out for a 20-year European put option, and would see an arbitrage opportunity if they could purchase

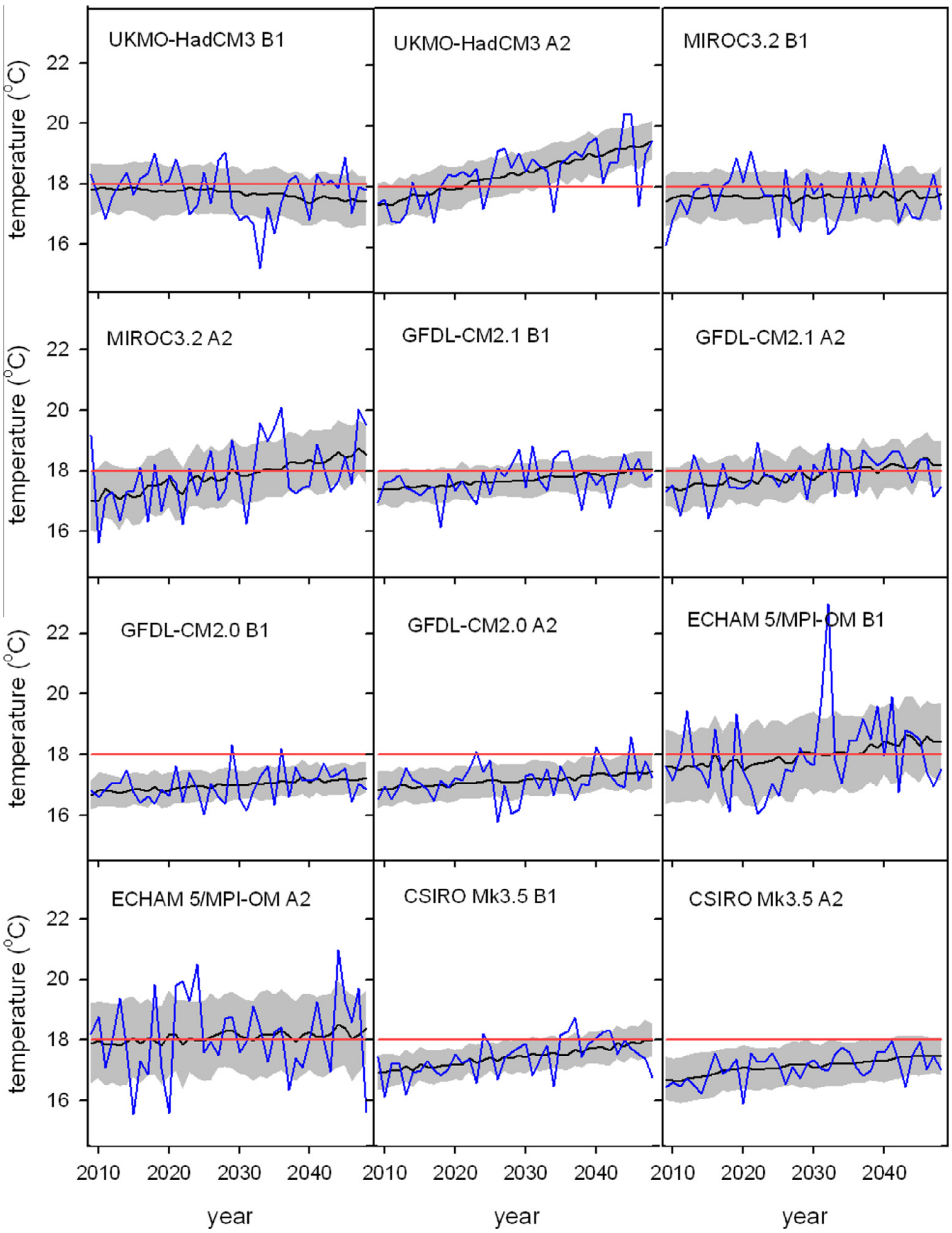

Fig. 1. Summer sea surface temperature forecasts for D'Entrecasteaux Channel Tasmania (43.05°S, 147.18°E). Each panel represents an indicated downscaled GCM trajectory (blue) and the mean (black) ± 1 SD (grey) forecast from 100 simulated ARMA models using a multivariate parameter sample based on mean and variance–covariance of estimated ARMA parameter coefficients (Table 1). The red line is the 18 °C strike. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the contract at the lower price of $45.85. Thus, such a party should either "put up" their capital for climate adaptation, or not and "shut up".

A risk market in climate derivatives to support climate adaptation strategies requires discussion over the merits, risks and institutional design of the market. A more detailed assessment of climate change projections and associated uncertainties (Allen, 1999) would likely result. A risk market would also require the establishment of institutions such as clearinghouses to manage the risk associated with counter-party capability of settling their obligations.

Climate derivatives could be used to manage climate risk in other situations beyond coastal aquaculture. Bloch et al. (2011) describe a hypothetical example, based on projected sea level rise, that starts with a 'best estimate' in a coastal area of 100 cm, with 95% confidence that sea-level will be between 75 and 190 cm. If a party decides to proceed with a

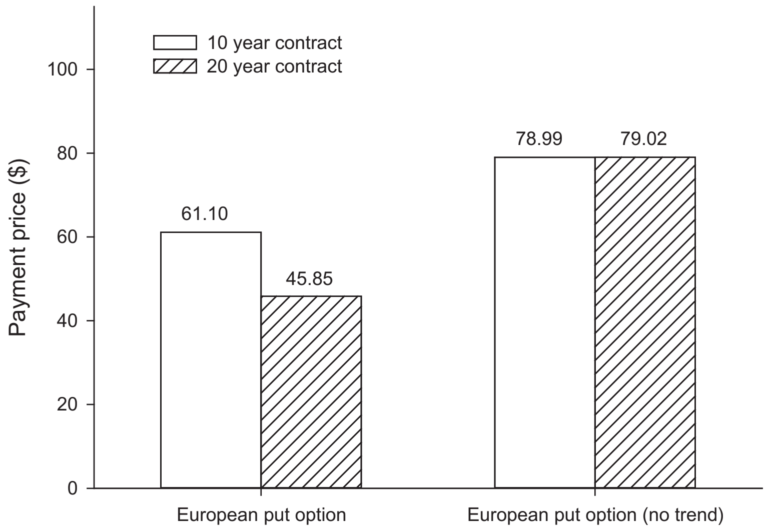

Fig. 2. Derivative prices for a 10 and 20-year to maturity European put option with an 18 °C strike value, calculated from an ensemble of downscaled summer SST forecasts in D'Entrecasteaux Channel, Tasmania (43.05 S, 147.18 E) obtained from ARMA simulations with and without the temperature long-term trend.

development, but is unsure what sea-level specification to target, they might opt to over-engineer the coastal defence to 190 cm, and risk wasting their capital if less than 100 cm rise eventuates. Likewise, under-specifying the coastal defence and building a 75 cm defence, also risks serious financial consequences should the coastal defences be breached.

A derivative contract could be established whereby the developer takes a proactive position on climate change risk, and writes a call option for a strike of 100 cm sea level, sells it to investors, and uses the payment fee to build a coastal defence to the 190 cm specification. If sea-level rise is below 100 cm, then the financial loss incurred by the developer from over-specifying is offset by the investor payment fees used to finance the development. If sea-level rise is above 100 cm and the defences prevent the economic loss as specified, then the developer must payout the option contract to the investor. This pay-out, however, would be supported by the economic productivity of the operational development, which would cease without the additional coastal defences.

All climate forecasts are contingent on future socio-economic conditions, including potential decisions to mitigate. We used data integrated across two emission scenarios with equal weightings, but could have conditioned a derivative on a different set of scenarios, weights or mitigation strategy, potentially using an integrated assessment model (IAM) coupled to a process-based climate model (Gunasekera et al., 2008). The resulting derivative prices would permit comparison of mitigation strategies under a climate policy objective, such as emissions commitments, and provide a basis for monitoring and revising policies.

Conclusion

Climate derivatives, priced using process-based climate models, can be used to quantify and manage climate risk in the future (Bloch et al., 2010). They can be widely applied wherever there is a well-defined index, threshold, and a basis for predicting future probabilistic outcomes. Key benefits of the derivative prices calculated in this manner are that they: (1) represent a quantifiable risk indicator for adaptation and planning purposes (Linnenluecke and Griffiths, 2010; Stokes et al., 2010) and (2) offer a starting point for raising capital to finance adaptation strategies.

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