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Handling Weather Related Risks Through the Financial Markets: Considerations of Credit Risk, Basis Risk, and Hedging

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Abstract

The profits of many businesses are strongly affected by weather related events, and insurance against weather related risks (acts of God) has been a traditional domain for transfer of (certain) of these risks. Recent innovations in the capital market have now provided financial instruments to transfer and hedge some of these risks. Unlike insurance solutions, however, using these financial derivative instruments creates a situation in which the return to the purchaser of the instrument is no longer perfectly correlated with the loss experienced. Such a mismatch creates new risks which must be examined and evaluated as part of ascertaining cost effective risk management plans. Two newly engendered risks, basis risk (the risk created by the fact that the return from the financial derivative is a function of weather at a prespecified geographical location which may not be identical to the location of the firm) and credit risk (the risk that the counterparty to the derivative contract may not perform), are analyzed in this article. Using custom tailored derivatives from the over the counter market can decrease basis risk, but increases credit risk. Using standardized exchange traded derivatives decreases credit risk but increases basis risk. Here also the effectiveness of using hedging methods involving forwards and futures having linear payoffs (linear hedging) and methods using derivatives having nonlinear payoffs such as those involving options (nonlinear hedging) for the purpose of hedging basis risk are examined jointly with credit risk.

Introduction

Many businesses have large and increasing financial exposures to uncertain global weather conditions. In addition to obvious examples of weather affected product

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demand in the energy and power industries, agriculture,[1] and recreational businesses (skiing, scuba diving, etc.), other economic sectors such as insurance, tourism, airlines, and retail businesses can also be directly or indirectly affected by weather (e.g., see Dischel, 1998; Zeng, 2000). Indeed, according to Dischel (1998), the three-quarters of the firms worldwide have a need to manage the financial consequences of weather risks.

What is a weather related financial gain to some (e.g., heavy snow for Winter Park Ski Resort located close to Denver, Colorado) may create a financial loss to others (e.g., United Airlines with hub transfer location in the Denver airport). Traditionally, while individually both firms might insure such risk, the negative correlation that exists between their respective profitability conditional on weather raises the possibility that the two might both be better off if they could somehow "trade" their weather risk exposures. Thus, in such circumstances, the opportunity exists to create a hedge for such weather related risks such that the gains to one firm are used to offset losses to the other. The realization of such a hedging possibility gave rise in 1997 (following the deregulation of American energy and power industries) to a capital market financial instrument (the weather derivative) developed to allow companies to trade such risks and hedge weather risks caused by noncatastrophic weather events including temperature, humidity, rainfall, snowfall, stream flow, and wind.[2] The developed financial derivative instrument (called a weather derivative) pays to the holder an amount contingent upon some specified function of an observable weather index, just like a stock index based option (like one on the S&P 500) pays off based upon the value of a prespecified stock index. Weather derivatives appeal to businesses (including insurance firms) that could be adversely affected by unanticipated weather swings in the same way that interest rate or foreign exchange rate futures and options appeal to businesses (including insurance firms) that could be adversely affected by unanticipated changes in interest rates or foreign exchange rates.

Since the inception of the weather derivative market, the number and type of market participants have continually expanded. A variety of firms now offer weather risk management products, including integrated energy trading firms, insurance companies, hedge funds, and investment and commercial banks. In our models, the issuers of weather derivatives can be an investment bank, an insurance company, or an energy trading company. Hedgers using weather derivatives might seek to manage their risks for a variety of reasons: tax, nondiversifiable stakeholders, costly external financing and financial distress, and some principal-agent problems such as asset substitution and debt overhang (Doherty and Richter, 2002). By utilizing hedging to

[1] In agricultural markets, crop insurance, derivatives on crop yields, and some revenue contracts are available to manage quantity (or yield) risks for farmers. See, for example, Li and Vukina (1998), Coble, Heifner, and Zuniga (2000), Tomek and Peterson (2001), Hennessy (2002), and Mahul and Wright (2003).

[2] Weather risk is mainly a quantity risk, which is the profit risk resulting from a change in the demand for goods because of weather. Financial derivatives simply based on price, if such instruments were to be available, might not be appropriate to hedge quantity risks unless price and quantity demanded were highly correlated. Excluded from the weather derivatives developed are weather related catastrophic risks (CAT risks) caused by hurricanes, tornadoes, windstorms, etc., which are already addressed by CAT derivatives.

stabilize variability in their cash flows, even at a financial premium, firms benefit in terms of risk aversion and after tax profitability (cf. Harrington and Niehaus, 2003).

Weather derivatives, however, differ from more conventional financial derivatives (stock option, commodity futures, etc.) in that there is no primal original, negotiable (tradable) underlying asset or price series which forms the basis of the contract, consequently making traditional arbitrage pricing methods problematic.[3] While more familiar financial derivatives are based on asset share prices, bonds, exchange rates, or currency rates, the underlying index or series upon which the weather derivative is based involves a nonmarket traded quantification of observed weather recordings, and it is this weather derived series of numbers (index) which governs when and how payouts on the contract will occur.

The most common weather derivatives currently available in the capital market are based on a synthetic index created from observed temperature changes at a specific geographic location. The underlying indices typically try to address losses caused by either "too hot" weather, (measured by the series called cooling degree days, CDDs), or "too cold weather," (measured by the series called heating degree days, HDDs). Temperatures are measured at a particular place and time specified in the contract. Starting with 65 °F as the norm, derivatives used to hedge against extreme prolonged heat use a measure that defines a daily CDD as Max (0, daily average temperature –65 °F). For derivatives used to hedge "coldness," a daily HDD is computed as Max (0, 65°F – daily average temperature). Since long stretches of foul weather are more destructive than isolated single days of bad weather (which might be endured with little financial impact), most temperature based weather derivatives are based on an accumulation of HDDs or CDDs during a specified period (contract period), say, 1 week, one calendar month, or a winter/summer season. To calculate the degree days over a period, one simply aggregates the daily degree days for each day in that period.

Currently, most of the weather derivatives are over-the-counter (OTC) contracts[4] (Banks, 2002). Johnson and Stulz (1987) suggest that default risk on the part of the counter party is often a possibility that must be taken seriously, so that when employing such OTC instruments one must be aware of the possibility that the individual on the other side of the transaction may not perform. This is a risk known as credit risk, and is an intrinsic characteristic of OTC weather derivatives. The topic of credit risk has attracted considerable attention in the weather risk market since Enron's bankruptcy,[5] with analysts now being increasingly focused on the credit quality of energy trading firms. In fact, several firms involved in this market have been downgraded, some to junk status (Sloan, Palmer, and Burrow, 2002) because of this risk.

There are many models which have been developed to predict financial distress and bankruptcy (see, e.g., Altman, 1968; Brockett et al., 1994; Altman and Saunders, 1997; Cummins, Grace, and Phillips, 1999; Carson and Hoyt, 2000) and these are of relevance

[3] Accordingly, the weather derivative market is an incomplete market without arbitrage pricing possibility. Several incomplete market pricing models have been developed to value weather derivatives (see, e.g., Davis, 2001; Barrieu and Karoui, 2002).

[4] See Climetrix, Risk Management Solutions (RMS), Inc., at www.climetrix.com.

[5] Enron was the initiator of the weather derivatives market and the largest dealer in this market before the company's demise.

in the context of assessing credit risk. This assessment can in turn be incorporated into pricing models to price financial derivate contracts subject to credit risk (see, e.g., Johnson and Stulz, 1987; Jarrow and Turnbull, 1995; Jarrow and Yu, 2001).

Studies have also analyzed optimal hedging strategies when the hedger faces nonperformance or credit risk (see, e.g., Hentschel and Smith, 1997; Cummins and Mahul, 2003a), and the demand for insurance by policyholders who purchase insurance from credit-risky insurers (see, e.g., Tapieo, Kahane, and Jacque, 1986; Doherty and Schlesinger, 1990; Cummins and Mahul, 2003b).

An alternative to the credit risk imbued OTC weather derivatives is to use standardized exchanged traded contracts. Although most trading in the weather market is still over-the-counter, some standardized weather derivative contracts are now listed on the Chicago Mercantile Exchange (CME)[6] and the London International Financial Futures and Options Exchange (LIFFE).[7] Exchange-based weather transactions have grown substantially since their introduction in 1999.[8] The exchanged-based transactions provide additional price transparency, and mitigate counterpart default risk through the promise of the clearing house.

However, there is a compromise in moving to exchange traded derivatives. In the process of creating standardized contracts, the place and time specified in the contract may not be a completely appropriate place and time for all potential users as it could be for the OTC derivatives. For example, if a derivative contract measures snowfall (or cooling degree days) at the Denver airport, it may not provide a complete hedge for a ski resort located in Winter Park miles outside Denver, and vice versa. This mismatch between the specific details forming the basis of the weather derivate instrument (time, place, and weather index) and the details pertinent to the firm intending to use the instrument to hedge their weather risk is called "basis risk." Hedgers trading in the standardized weather derivatives must bear basis risk unless the standardized instrument is based precisely on the location and needs of the hedging firm (i.e., use a weather index local to the firm). While the OTC weather derivative market includes most U.S. cities, the exchange-based market includes only about 15 cities, so participants wishing to manage weather exposures in cities not listed by the exchanges face basis risk (Considine, 2000).

Basis risk is an important concern for firms hedging with standardized exchange traded contracts. Ederington (1979) shows that the degree of basis risk a firm faces in using a hedging instrument can have a substantial effect on the usefulness of the instrument in reducing risk. Haushalter (2000) finds that the likelihood of hedging

[6] CME offers futures and options based on indexes of HDDs and CDDs for selected population centers and energy hubs with significant weather-related risks throughout the United States and for some European cities. For details, see Weather Products, Chicago Mercantile Exchange, at http://www.cme.com/prd/wec.

[7] LIFFE weather future contracts are settled against monthly and winter season indexes based on daily average temperatures in three European cities: London (Heathrow), Paris (Orly), and Berlin (Tempelhof). For details, see the London International Financial Futures and Options Exchange at www.liffe.com.

[8] See Weather Products, Chicago Mercantile Exchange, at www.cme/prd/wec.

of the oil and gas producers is related to the basis risk associated with hedging instruments. Many other works discuss optimal hedging with some source of basis risk where only price based derivatives are available to manage price risks (see, e.g., Hill and Schneeweis, 1982; Figlewski, 1984; Chang and Shanker, 1986; Moser and Helms, 1990; Castelino, 1992; Briys, Crouhy, and Shlesinger, 1993; Moschini and Lapan, 1995; Garcia and Sanders, 1996; Mahul, 2002; Miffre, 2004). Some studies in agricultural economics analyze optimal hedging with some source of basis risk where instruments are also available to manage yield and/or revenue risks (see, e.g., Poitras, 1993; Vukina, Li, and Holthausen, 1996; Li and Vukina, 1998; Coble, Heifner, and Zuniga, 2000). The basis risk of some derivatives with exotic underlying indices, such as insurance derivatives, has also been analyzed in the literature (see, e.g., D'Arcy and France, 1992; Harrington, Mann, and Niehaus, 1995; Harrington and Niehaus, 1999; Major, 1999; Cummins, Lalonde, and Phillips, 2004).

Basis risk opens up the possibility of a market involving the differential between indices on exchange-quoted locations and those on locations not quoted on the exchanges. To possibly reduce the magnitude of basis risk, the hedger can use these so called "basis derivatives" (including basis swaps and basis options), to hedge basis risk (see, e.g., Considine, 2000; MacMinn, 2000). Basis derivatives are written on the difference between two prices, two indices, etc. With respect to weather derivatives, basis derivatives are written on the difference of the weather indices at two different locations. Intuitively, combining the standardized exchange traded weather derivatives and the OTC basis weather derivatives (which are written on the differentials between the weather derivatives at two cities) may extend the possibility set of financial instruments available for hedging and consequently enhance the efficiency gains obtained by hedging.

Doherty and Richter (2002) analyze risk-sharing efficiency effects and the tradeoff between basis risk and moral hazard due to the joint use of index-linked insurance derivatives (involving some basis risk) and indemnity gap insurance (involving some moral hazard). Following the methodology of Doherty and Richter (2002), this article analyzes risk-sharing efficiency effects of various basis hedging strategies: the joint use of the standardized exchange traded weather derivatives (which are subject to basis risk) and some OTC basis weather derivatives (which are subject to credit risk).

Previous research on optimal hedging with sources of basis risk have investigated hedging behavior in incomplete markets wherein basis risk is not completely hedgeable (see, e.g., Briys, Crouhy, and Shlesinger, 1993; Poitras, 1993; Moschini and Lapan, 1995; Vukina, Li, and Holthausen, 1996; Li and Vukina, 1998; Coble, Heifner, and Zuniga, 2000; Mahul, 2002). Basis risk can be traded (Considine, 2000), and this article extends the literature by allowing hedgers to use OTC basis weather derivatives to further manage basis risk. While basis weather derivatives can be used to manage basis risk, they also bring the hedgers some credit risk because basis weather derivatives are OTC contracts.

Previous research on optimal hedging and insurance demand or credit risk (see, for example, Tapieo, Kahane, and Jacque, 1986; Doherty and Schlesinger, 1990; Hentschel and Smith, 1997; Cummins and Mahul, 2003a, 2003b), have not analyzed the impact of basis risk nor the tradeoff between basis risk and credit risk (as is done in this article). Another contribution to the literature is our incorporation of nonhedgeable credit risk into our hedging models with hedgeable basis risk. Basis hedging strategies using both exchange traded contracts and OTC basis contracts are compared with local hedging strategies in terms of hedging effectiveness. Local hedging strategies are defined as hedging using OTC local weather derivatives—weather derivatives written on a weather index local to the firm. Local weather derivatives are supposed to have no basis risk but are subject to credit risk. Simulations are conducted to analyze the impact of weather risk, basis risk, and credit risk on optimal hedging and the determinants of hedging behavior and hedging effectiveness.

This article is organized as follows. The next section sets up the hedging models. The section "Basis Hedging Behavior" analyzes hedging behavior, and the section "Basis Hedging Effectiveness" measures basis hedging effectiveness. The article concludes with a short summary and ideas for future research.

MODEL SPECIFICATION AND BASIC RESULTS

This article analyzes the basis hedging problem for the U.S. power market. Deregulation in the United States has given the power industry freedom to conduct its business in a more rational way, but at the same time exposes the industry to price and quantity risks.[9] Variability in weather conditions had always been recognized as one of the most significant factors affecting power consumption, however, the effects of unpredictable seasonal weather patterns had previously been absorbed and managed within a regulated, monopoly environment. With deregulation, the various participants in the process of producing, marketing, and delivering power to U.S. households and businesses were left to confront weather as a new and significant risk to their bottom line. While financial instruments for managing the risk of price volatility of power have been available for a while, the advent of weather derivatives represents an interesting departure for hedging the risk of power demand volatility.

Power producers facing quantity risk (demand risk), which is primarily caused by weather events, are assumed to choose weather derivatives to extremize an objective function which models their terminal wealth one period later. In this article, we do not consider price risk, so the wealth hedging problem reduces to the problem of hedging weather related quantity risk only.[10] The hedgers can use local hedging strategies

[9] See Brown and Toft (2002) for a discussion of how firms should hedge when faced with both price and quantity risks. Gay, Nam, and Turac (2002) also discuss the use of linear and nonlinear hedging in the face of price and quantity risk.

[10] In this article, we only consider quantity uncertainty and the effectiveness of weather derivatives to manage this quantity risk. The perfect model should include both quantity and price risk: price risk and quantity risk + price derivatives (with basis risk and credit risk) + quantity derivatives (with basis risk and credit risk). But this perfect model involves repetitive analyses on the tradeoff between basis risk and credit risk for both price hedging and quantity hedging. To focus our analyses on basis risk and credit risk, we assume that price risk has been totally hedged by price derivatives, a similar assumption to that in Mahul (2002) and Cummins and Mahul (2003a) who assume that quantity is nonrandom and analyze price hedging only. And our hedgeable model boils down to quantity risk + quantity derivatives (with basis risk and credit risk) and we analyze only quantity hedging with consideration of basis risk and credit risk.

with OTC local weather contracts or use basis hedging strategies with both exchange traded weather contracts and OTC basis weather contracts. The basis hedging strategy allows the hedger to use a weather derivative based on a standardized exchange-listed weather index. If the correlation between the standardized weather index and the hedger's demand quantity is less than one, there is some basis risk. The hedger can use a separate OTC weather derivative (basis derivative) to cover the difference between the standardized weather index used on the exchange and hedger's local weather index, which is assumed to have a higher correlation than the standardized weather index, or a perfect correlation, with the hedger's quantity demand. Let t_e denote the standardized exchange-listed weather temperature index, let the local weather index be denoted by t_l, and let the basis weather index (the difference) be denoted by $t_d = t_l - t_e$. Strategies using both linear hedging (selling weather forwards and/or futures short positions) and nonlinear hedging (buying weather put options long positions) are allowed.

As mentioned previously, weather derivatives written on local weather indices and basis indices are over-the-counter contracts and bear some credit risk. Let θ denote the payoff proportion from a weather derivative paid to the hedgers. In our analyses, we take the random variable θ to be either 1 or 0 (i.e., full contract performance or complete nonperformance).[11] Define the probability distribution of θ as $\text{Prob}(\theta = 1) = p$ and $\text{Prob}(\theta = 0) = 1 - p$ so that credit risk (the risk of nonperformance of the counter party) is represented by $\text{Prob}(\theta = 0) = 1 - p$. We assume that θ is independent of all the other stochastic variables: q, t_l, and t_e.[12] The hedgers' payoffs from the weather derivatives, with consideration of credit risk, are shown in Table 1. k_l, k_d, and k_e are tick sizes.

The tick sizes for all the weather derivatives considered in this article are measured in the unit of power demand (q), and are normalized so as to be assumed to be 1. The weather risk market is assumed to be unbiased; that is, the premium of the weather derivative is equal to the expected value of its payoff.[13]

[11] In this article, credit risk is assumed to be dichotomous. This assumption fits very well in the mean-variance framework. For example the hedger's variance after incorporating this dichotomous credit risk variable is: $\text{Var}(\theta x) = pEx^2 - p^2(Ex)^2 = p[Ex^2 - (Ex)^2] + (Ex)^2 \times [p - p^2] \approx p\text{Var}(x)$ since it is reasonable to assume that the probability of nondefault p very high for most issuers, so that $p \approx p^2$. Consequently, if the hedger is comfortable with the mean-variance framework without incorporating credit risk, the mean-variance framework is also acceptable to the hedger after the incorporation of the dichotomous credit risk. An extension to the situation wherein θ has a continuous distribution supported on [0,1] is possible but not done here.

[12] Issuers generally write a large portfolio to take advantage of geographic diversification and hedging effects and the contracts issued to an individual hedger only accounts for a small part in this portfolio. Accordingly, it is reasonable to assume that the issuer's default/credit risk is independent of a hedger's individual performance. In addition, Hentschel and Smith (1997) indicate that credit risk may not be a severe problem as far as the derivatives are concerned, but insolvency can result from other "agency costs." In addition, there are also some other important variables, such as macroeconomic factors, contributing to an issuer's bankruptcy. It is also reasonable to assume that these agency costs and macroeconomic factors are independent of a hedger's individual performance.

[13] Transaction costs of weather trading are not considered in this article.

TABLE 1
Hedgers' Payoffs From Weather Contracts With Consideration of Credit Risk

	Forwards/Futures (Short)	Put Options (Long)
Local (OTC) weather index	$\theta k_l \max(T_l - t_l, 0) - k_l \max(t_l - T_l, 0)$	$\theta k_l \max(T_l - t_l, 0)$
Basis weather index	$\theta k_d \max(T_d - t_d, 0) - k_d \max(t_d - T_d, 0)$	$\theta k_d \max(T_d - t_d, 0)$
Standardized (exchange) weather index	$k_e(T_e - t_e)$	$k_e \max(T_e - t_e, 0)$

The weather indices considered here involve HDDs and CDDs, and the corresponding weather derivatives are based on the accumulation of HDDs or CDDs (or the difference between HDDs/CDDs for basis weather derivatives) during a specified contract period, usually, 1 week, one calendar month, or a winter/summer season. Thus, for the derivative, the daily degree days in a specified period are aggregated so that the underlying weather index upon which the derivative is based, t, is

$$t = \sum_{i=1}^{n} \mathrm{HDD}_i \text{ or } t = \sum_{i=1}^{n} \mathrm{CDD}_i, \tag{1}$$

where HDD_i and CDD_i are heating degree day and cooling degree day of day i, respectively, and n is the number of days in the weather contract period.

In our hedging models, we employ the mean-variance objective function[14]

$$u(W \mid \theta) = E(W \mid \theta) - \lambda\sigma^2(W \mid \theta) \tag{2}$$

with risk aversion parameter $\lambda > 0$ and where W denotes the hedger's terminal wealth. Higher expected wealth improves firm value, while higher volatility imposes costs due to increases in the likelihood of financial distress and/or effects on future investment incentives (Bessembinder and Lemmon, 2002). The hedger seeks to maximize the utility of terminal wealth at date one by using weather derivatives to manage their weather exposures.

Linear Hedging With Futures and Forwards

The final wealth of a hedger using linear local hedging (hedging using OTC local weather forwards written on local weather indices) without consideration of credit risk is

$$W = q - E[h_{l-ll}(T_l - t_l)] + h_{l-ll}(T_l - t_l), \tag{3}$$

[14] The mean-variance utility framework has been widely cited in the literature (see, e.g., Rolfo, 1980; Duffie and Richardson, 1991; Hirshleifer and Subramanyam, 1993; Vukina, Li, and Holthausen, 1996; Doherty and Richter, 2002; Bessembinder and Lemmon, 2002). But other objective functions could be used to ascertain the robustness of the comparative static results for hedge ratios and hedging effectiveness derived in this article.

while the hedger using linear basis hedging (hedging using the combination of exchange traded weather futures and OTC basis weather forwards) has a final wealth given by

$$W = q - E[h_{e-lb}(T_d - t_e)] - E[h_{d-lb}(T_d - t_d)] + h_{e-lb}(T_e - t_e) + h_{d-lb}(T_d - t_d), \tag{4}$$

where $t_d = t_l - t_e$ is the index for the OTC basis forward, and T_l, T_e, T_d are the corresponding strike levels of the local, exchange traded, and basis weather derivatives, respectively. The subscript *ll* designates "linear local hedging" using OTC local weather contracts, and *lb* denotes "linear basis hedging" involving standardized exchange traded instruments and OTC basis contracts. We denote by h_{l-ll}, h_{e-lb}, h_{d-lb} the hedge ratios of OTC local weather forwards, exchange-quoted weather futures, and OTC basis weather forwards, respectively. h_{l-ll}, h_{e-lb}, h_{d-lb} are positive when the hedger has short positions in these forwards and futures.

Linear Local Hedging With Credit Risk. Upon consideration of the credit risk associated with OTC contracts, the final wealth associated with linear local hedging using OTC local weather forwards becomes (compare Table 1)

$$W = q - E\left[h_{l-ll}\left(\theta r_l^p - r_l^c\right)\right] + h_{l-ll}\left(\theta r_l^p - r_l^c\right), \tag{5}$$

where for notational convenience we have abbreviated the returns on put and call derivatives by $r_l^p = \max(T_l - t_l, 0)$, and $r_l^c = \max(t_l - T_l, 0)$, respectively. Using the mean-variance objective function, the optimal hedging problem for the firm using the weather derivatives is $\mathrm{MAX}_{h_{l-ll}} E(W|\theta) - \lambda\sigma^2(W|\theta)$. From this, one derives the optimal hedge ratio as[15]

$$h^*_{l-ll} = \frac{-p\sigma_{q,r_l^p} + \sigma_{q,r_l^c}}{p\sigma^2_{r_l^p} + \sigma^2_{r_l^c} + (p - p^2)\mu^2_{r_l^p} - 2p\sigma_{r_l^p,r_l^c}}. \tag{6}$$

When there is no credit risk, that is when $p = 1$, this optimal hedge ratio is the same as the classic Ederington result (Ederington, 1979).[16]

Linear Basis Hedging With Credit Risk. Upon consideration of credit risk, the final wealth associated with using linear basis hedging with both exchange traded futures and OTC basis forwards is

[15] In this article, we use usual statistical notation μ_x or $E(x)$ for the expected value of x, σ_x^2 for the variance of x, $\sigma_{x,y}$ for the covariance of x and y, and $\rho_{x,y}$ for the correlation coefficient of x and y.

[16] Analytical results about the determinants of almost all the hedge ratios when nonlinear contracts are involved are not generally available, so in such situations hedging behaviors are analyzed in the section "Basis Hedging Effectiveness" mainly using simulations.

$$
\begin{aligned}
W = q &- E[h_{e-lb}(T_e - t_e)] - E\left[h_{d-lb}\left(\theta r_d^p - r_d^c\right)\right] \\
&+ h_{e-lb}(T_e - t_e) + h_{d-lb}\left(\theta r_d^p - r_d^c\right),
\end{aligned}
\tag{7}
$$

where the put and call returns based upon the difference in indices (basis derivatives) are denoted by $r_d^p = \max(T_d - t_d, 0)$, and $r_d^c = \max(t_d - T_d, 0)$, respectively. Again using the mean-variance objective function yields the optimal hedging problem $\mathrm{MAX}_{h_{e-lb}, h_{d-lb}} E(W \mid \theta) - \lambda\sigma^2(W \mid \theta)$. The maximizing optimal hedge ratios are

$$
h_{d-lb}^* = \frac{\sigma_{q,t_e}\left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right) + \sigma_{t_e}^2\left(\sigma_{q,r_d^c} - p\sigma_{q,r_d^p}\right)}{\sigma_{t_e}^2\left[p\sigma_{r_d^p}^2 + (p - p^2)\mu_{r_d^p}^2 + \sigma_{r_d^c}^2 - 2p\sigma_{r_d^p,r_d^c}\right] - \left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)^2}
\tag{8}
$$

and

$$
h_{e-lb}^* = \frac{\left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)\left(\sigma_{q,r_d^c} - p\sigma_{q,r_d^p}\right) + \sigma_{q,t_e}\left[p\sigma_{r_d^p}^2 + \sigma_{r_d^c}^2 + (p - p^2)\mu_{r_d^p}^2 - 2p\sigma_{r_d^p,r_d^c}\right]}{\sigma_{t_e}^2\left[p\sigma_{r_d^p}^2 + (p - p^2)\mu_{r_d^p}^2 + \sigma_{r_d^c}^2 - 2p\sigma_{r_d^p,r_d^c}\right] - \left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)^2}.
\tag{9}
$$

Since the OTC basis forward is intended to be used in conjunction with the exchange traded weather future contract, it is of interest to know when these two contracts yield the same hedge ratio. Upon calculation we find that h_{d-lb}^* is equal to h_{e-lb}^* if and only if

$$
\begin{aligned}
&\sigma_{q,t_e}\left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right) - \left(p\sigma_{q,r_d^p} - \sigma_{q,r_d^c}\right)\left(\sigma_{t_e}^2 - p\sigma_{t_e,r_d^p} + \sigma_{t_e,r_d^c}\right) \\
&\quad = \sigma_{q,t_e}\left[p\sigma_{r_d^p}^2 + \sigma_{r_d^c}^2 + (p - p^2)\mu_{r_d^p}^2 - 2p\sigma_{r_d^p,r_d^c}\right].
\end{aligned}
\tag{10}
$$

Nonlinear Hedging With Put Options

Ignoring credit risk at the onset, the final wealth resulting from using nonlinear local hedging (hedging using OTC local put options written on local weather indices) is

$$
W = q - E\left(h_{l-nl} r_l^p\right) + h_{l-nl} r_l^p
\tag{11}
$$

and the final wealth obtained using nonlinear basis hedging (hedging using the combination of exchange traded put options and OTC basis put options) is

$$
W = q - E\left(h_{e-nb} r_e^p\right) - E\left(h_{d-nb} r_d^p\right) + h_{e-nb} r_e^p + h_{d-nb} r_d^p,
\tag{12}
$$

where as before, the returns on the put options are $r_l^p = \max(T_l - t_l, 0)$, $r_e^p = \max(T_e - t_e, 0)$, and $r_d^p = \max(T_d - t_d, 0)$, and T_l, T_e, T_d denote the corresponding strike levels of these weather derivatives. Here the superscript p designates "put option," the subscript *nl* denotes "nonlinear local hedging," while *nb* denotes "nonlinear basis hedging." The hedge ratios of local, standardized exchange-quoted weather put options and basis weather put options, respectively are denoted by h_{l-nl}, h_{e-nb}, h_{d-nb}. These hedge ratios are positive when the hedger has long positions in these options.

Nonlinear Local Hedging With Credit Risk. Incorporating the credit risk consideration into the analysis, the final wealth obtained using nonlinear local hedging with OTC local put options is

$$W = q - E\left(\theta h_{l-nl} r_l^p\right) + \theta h_{l-nl} r_l^p. \tag{13}$$

The mean-variance optimal hedging problem then becomes: $\mathrm{MAX}_{h_{l-nl}} E(W|\theta) - \lambda\sigma^2(W|\theta)$, and the optimal hedge ratio is determined to be

$$h_{l-nl}^* = \frac{-\sigma_{q,r_l^p}}{\sigma_{r_l^p}^2 + (1-p)\mu_{r_l^p}^2}. \tag{14}$$

Note that as one would expect, this hedge ratio decreases in credit risk, (represented by $1 - p$). That is, a higher credit risk implies less use of the OTC local weather put option, other things remaining constant.

Nonlinear Basis Hedging With Credit Risk. Similar to the previous calculations, with nonlinear basis hedging using both exchange traded weather put options and OTC basis put options the final wealth taking into consideration credit risk, is

$$W = q - E\left(\theta h_{d-nb} r_d^p\right) - E\left(h_{e-nb} r_e^p\right) + h_{e-nb} r_e^p + \theta h_{d-nb} r_d^p. \tag{15}$$

The optimal hedging problem becomes $\mathrm{MAX}_{h_{e-nb},h_{d-nb}} E(W|\theta) - \lambda\sigma^2(W|\theta)$, and the optimal hedge ratios are

$$h_{d-nb}^* = \frac{\sigma_{q,r_e^p}\sigma_{r_e^p,r_d^p} - \sigma_{q,r_d^p}\sigma_{r_e^p}^2}{\sigma_{r_e^p}^2\sigma_{r_d^p}^2\left(1 - p\rho_{r_e^p,r_d^p}^2\right) + (1-p)\sigma_{r_e^p}^2\mu_{r_d^p}^2} \tag{16}$$

and

$$h_{e-nb}^* = \frac{(p-1)\mu_{r_d^p}^2\sigma_{q,r_e^p} + p\sigma_{q,r_d^p}\sigma_{r_e^p,r_d^p} - \sigma_{q,r_e^p}\sigma_{r_d^p}^2}{\sigma_{r_e^p}^2\sigma_{r_d^p}^2\left(1 - p\rho_{r_e^p,r_d^p}^2\right) + (1-p)\sigma_{r_e^p}^2\mu_{r_d^p}^2}. \tag{17}$$

The basis weather put option is intended to be used to complement the exchange traded put option contract. Consequently it is of interest to know when these two contracts have the same magnitude hedge ratio. When $\mu^2_{r_d^p}\sigma_{q,r_e^p} + \sigma_{q,r_d^p}\sigma_{r_e^p,r_d^p} \neq 0$, we find h^*_{d-nb} is equal to h^*_{e-nb} if and only if

$$p = \frac{\sigma_{q,r_e^p}\left(\sigma_{r_e^p,r_d^p} + \mu_{(r_d^p)^2}\right) - \sigma_{q,r_d^p}\sigma^2_{r_e^p}}{\mu^2_{r_d^p}\sigma_{q,r_e^p} + \sigma_{q,r_d^p}\sigma_{r_e^p,r_d^p}}. \tag{18}$$

When $\mu^2_{r_d^p}\sigma_{q,r_e^p} + \sigma_{q,r_d^p}\sigma_{r_e^p,r_d^p} = 0$, we calculate that h^*_{d-nb} is equal to h^*_{e-nb} if and only if

$$\sigma_{r_e^p,r_d^p} = \frac{\sigma_{q,r_d^p}}{\sigma_{q,r_e^p}}\sigma^2_{r_e^p} - \mu_{(r_d^p)^2}. \tag{19}$$

BASIS HEDGING BEHAVIOR

In this section, we analyze the hedger's optimal position in the weather derivatives market. These analyses are useful in evaluating the factors that impact the hedging positions, as well as in evaluating the hedger's interest in the differential weather market and in the exchange traded weather contracts.

Suppose that the power producer's quantity risk can be decomposed into a systematic portion correlated with local weather index (weather risk) and nonsystematic idiosyncratic individual variation. This relationship may be written as $q = \alpha + \beta t_l + \varepsilon$, where $\varepsilon \sim N(0, \sigma^2_\varepsilon)$ is the nonsystematic quantity risk, which is independent of all the weather indices (t_l, t_e, t_d). Under this assumption, the optimal hedge ratios are restated in the Appendix.

To illustrate the determinants of the optimal hedge ratios, we performed a series of simulations. Specifically, we analyze the impacts of weather risk, basis risk and credit risk on the hedge ratios. We assume that weather indices are normally distributed.[17] Credit risk is represented by $1 - p$; the higher the probability p, the lower the credit risk. Weather risk is represented by the standard deviation of the local index (σ_{t_l}); the higher this standard deviation, the more volatile the weather and the higher the weather risk. Basis risk is characterized by the correlation between local weather index and the exchange-listed standard weather index (ρ_{t_l,t_e}); the higher this correlation, the lower the basis risk. The background risk (nonsystematic risk), represented by σ_ε, has no influence on hedge ratios. For our simulations the sensitivity coefficient β is assumed to be 1.

Throughout we assume that the forwards/futures contracts are "costless" in the sense that the strike level is equal to the expected value of the underlying index[18] and that the

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[17] This assumption is justified by the historical temperature data of the 10 U.S. cities listed on Chicago Mercantile Exchange (available at www.cme.com), and the data of regional indexes from the Risk Management Solutions Inc. (www.rms.com).

[18] Without credit risk, in an unbiased market, when the strike level T is equal to the expected value of the underlying index t, the premium for the future/forward is $E(T - t) = 0$, so it is costless. With credit risk, however, the premium is no longer zero, but rather $E[\theta \max(T_t - t_{l,} 0) - \max(t_t - T_t, 0)]$ in the unbiased market. "Costless" here only means that the strike level is equal to the expected value of the underlying index.

options are at the money, that is, the strike levels $T_l = \mu_{t_l}$, $T_e = \mu_{t_e}$, and $T_d = \mu_{t_d}$.[19] For all the simulations, we randomly generate 20,000 realizations of (t_e, t_l), and the hedge ratios were computed from these 20,000 realizations.[20] The hedge ratios obtained by simulation under different levels of credit risk $(1 - p)$, standard deviation of the local weather index, and the correlation between the local weather index and the exchange-listed weather index are reported in Tables 2–4.

For linear local hedging using OTC local weather forwards, the simulation results indicate that the hedge ratio h_{l-ll} on the OTC local weather forward contract increases in credit risk, and this hedge ratio converges to 1 as credit risk approaches 0. At first glance, it is a little surprising that the local weather forward will be used more with increases in credit risk. However, with consideration of credit risk, the local weather forward is divided into two options (a put option and a call option), and this contract is not costless anymore. The hedger will earn a premium by entering this contract. Consequently, with credit risk, the linear hedging strategy acts like the hedging strategy of selling a call option. With an increase of credit risk, the hedger will use more of the local forward to get more premiums from this contract.

The simulations show that standard deviation of the local weather index has no impact on the use of the OTC local forward contract. This reflects the fact that linear local hedging with OTC local weather forwards is just a perfect linear hedge "inflated" by credit risk, and, given the credit risk level, the hedge ratio on the OTC local forward is always the same regardless of the weather risk itself.

For linear basis hedging with both exchange traded futures and OTC basis forwards, the simulation results indicate that the hedge ratio h_{e-lb} (*lb* denotes "linear basis hedging") on the weather future contract decreases in credit risk. The sensitivity of this hedge ratio to credit risk is greater when weather risk is low (firm value has a low sensitivity to weather conditions) and basis risk is high (changes in the value of the exchange traded weather contract has a low correlation with changes in firm value). Generally, this hedge ratio decreases in basis risk, and the sensitivity of this hedge ratio to basis risk is smaller at low levels of credit risk. Overall, the hedgers have a higher demand for weather futures when credit risk is low, basis risk is low (changes in the value of the exchange traded weather contract has a high correlation with changes in firm value), and weather risk is high (firm value has a high sensitivity to weather conditions). The hedge ratio h_{d-lb} on the basis weather forward is convex in credit risk, initially decreasing and then increasing. The sensitivity of this hedge

[19] In this article, we focus on power producers who think that a risk occurs when their actual quantity demand is below the expected quantity demand (not a number higher or lower than the expected quantity demand). Expected quantity demand is a generally acceptable bottom line for some hedgers, and it is reasonable to fix the strike levels at the expected weather index levels. Also, when we incorporate credit risk into our hedging models, a forward is divided into a put option and a call option. The options' strike levels in the nonlinear hedging models are assumed to be at the money to be consistent with the linear hedging models where the forward (the combination of a put option and a call option) is generally "costless." It would be an interesting topic for future work to make the strike levels of both options and "forwards" as decision variables.

[20] In our analysis simulations using 5,000, 10,000, 20,000, and 50,000 repetitions were are all tried. We present results for the simulations using 20,000 repetitions herein.

TABLE 2
Hedge Ratios Under Different Levels of p and σ_{t_l}

	p				
	0.1	0.3	0.5	0.7	0.9
σ_{t_l}					
Linear hedging					
5	1.31	1.14	1.06	1.02	1.00
	0.26	0.27	0.30	0.36	0.56
	0.19	0.17	0.20	0.26	0.50
10	1.31	1.14	1.06	1.02	1.00
	0.59	0.60	0.65	0.73	0.88
	0.68	0.61	0.62	0.70	0.86
15	1.30	1.14	1.06	1.02	1.00
	0.81	0.81	0.85	0.90	0.96
	1.07	0.94	0.91	0.92	0.96
20	1.31	1.14	1.06	1.02	1.00
	0.90	0.91	0.93	0.95	0.98
	1.25	1.09	1.02	0.99	0.99
25	1.30	1.14	1.06	1.02	1.00
	0.96	0.97	0.97	0.98	0.99
	1.30	1.13	1.05	1.01	1.00
30	1.31	1.14	1.06	1.02	1.00
	1.01	1.01	1.01	1.01	1.00
	1.31	1.14	1.06	1.02	1.00
Nonlinear hedging					
5	1.03	1.11	1.18	1.29	1.40
	0.25	0.25	0.24	0.23	0.22
	−0.06	−0.07	−0.08	−0.09	−0.10
10	1.03	1.11	1.19	1.29	1.40
	0.51	0.51	0.52	0.53	0.53
	0.03	0.03	0.03	0.04	0.05
15	1.04	1.11	1.19	1.28	1.41
	0.78	0.80	0.82	0.87	0.91
	0.37	0.40	0.44	0.50	0.56
20	1.03	1.11	1.19	1.29	1.40
	1.05	1.08	1.11	1.16	1.22
	0.75	0.81	0.88	0.97	1.07
25	1.03	1.11	1.19	1.29	1.40
	1.29	1.31	1.33	1.34	1.39
	0.97	1.05	1.13	1.21	1.33
30	1.03	1.10	1.19	1.29	1.40
	1.52	1.53	1.53	1.51	1.49
	1.05	1.12	1.20	1.30	1.42

Note: The weather indices t_l and t_e are bivariate normally distributed. $\rho_{t_e,t_l} = 0.7$, $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, and $\sigma_{t_e} = 20$. All estimates are computed using 20,000 simulation runs. In each cell representing a combination of credit risk and standard deviation of the local weather index, the hedge ratio values are listed vertically downward in the order h_{l-ll}, h_{e-lb}, and h_{d-lb}, respectively, for linear hedging; and h_{l-nl}, h_{e-nb}, and h_{d-nb}, respectively, for nonlinear hedging.

TABLE 3
Hedge Ratios Under Different Levels of p and ρ_{t_e,t_l}

	p				
	0.1	0.3	0.5	0.7	0.9
ρ_{t_e,t_l}					
Linear hedging					
0.1	1.31	1.14	1.06	1.02	1.00
	0.54	0.56	0.63	0.73	0.89
	0.92	0.81	0.80	0.84	0.93
0.3	1.31	1.14	1.06	1.02	1.00
	0.64	0.66	0.72	0.81	0.92
	0.98	0.87	0.85	0.88	0.95
0.5	1.30	1.14	1.06	1.02	1.00
	0.73	0.75	0.79	0.85	0.94
	1.04	0.91	0.88	0.90	0.96
0.7	1.31	1.14	1.05	1.02	1.00
	0.80	0.82	0.85	0.90	0.96
	1.07	0.94	0.91	0.92	0.97
0.9	1.30	1.14	1.05	1.02	1.00
	0.86	0.86	0.89	0.92	0.97
	1.02	0.90	0.88	0.90	0.95
Nonlinear hedging					
0.1	1.04	1.10	1.19	1.28	1.40
	0.13	0.17	0.22	0.31	0.39
	0.39	0.43	0.47	0.53	0.61
0.3	1.03	1.10	1.19	1.28	1.40
	0.35	0.39	0.43	0.50	0.57
	0.41	0.45	0.50	0.56	0.64
0.5	1.04	1.11	1.19	1.29	1.40
	0.57	0.60	0.64	0.68	0.75
	0.41	0.45	0.50	0.56	0.63
0.7	1.03	1.10	1.18	1.28	1.40
	0.78	0.80	0.82	0.86	0.91
	0.37	0.41	0.45	0.50	0.57
0.9	1.03	1.11	1.18	1.29	1.41
	1.00	1.00	1.00	1.00	1.01
	0.05	0.04	0.06	0.06	0.07

Note: The weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20, \sigma_{t_l} = 15$, and $\sigma_{t_e} = 20$. All estimates are computed using 20,000 simulation runs. In each cell representing a combination of credit risk and correlation coefficient, the hedge ratio values are listed vertically downward in the order h_{l-ll}, h_{e-lb}, and h_{d-lb}, respectively, for linear hedging; and h_{l-nl}, h_{e-nb}, and h_{d-nb}, respectively, for nonlinear hedging.

ratio to credit risk is greater at low levels of weather risk. This hedge ratio is concave in basis risk, initially increasing and then decreasing. The sensitivity of this hedge ratio to basis risk is also greater at low levels of weather risk. The hedge ratio on the exchanged traded forward and the hedge ratio on the basis forward both increase in the standard deviation of the local index, in response to the desire to hedge more of the weather risk.

TABLE 4
Hedge Ratios Under Different Levels of ρ_{t_e,t_l} and σ_{t_l}

	ρ_{t_e,t_l}				
	0.1	0.3	0.5	0.7	0.9
σ_{t_l}					
Linear hedging					
5	1.02	1.02	1.02	1.02	1.02
	0.30	0.34	0.36	0.36	0.31
	0.33	0.34	0.31	0.26	0.12
10	1.02	1.02	1.02	1.02	1.02
	0.60	0.67	0.71	0.74	0.70
	0.68	0.72	0.72	0.70	0.54
15	1.02	1.02	1.02	1.02	1.02
	0.74	0.80	0.85	0.90	0.92
	0.84	0.88	0.90	0.92	0.90
20	1.02	1.02	1.02	1.02	1.02
	0.80	0.87	0.92	0.95	0.99
	0.92	0.95	0.98	0.99	1.01
25	1.02	1.02	1.02	1.02	1.02
	0.83	0.90	0.94	0.98	1.02
	0.95	0.98	1.00	1.02	1.01
30	1.02	1.02	1.02	1.02	1.02
	0.85	0.92	0.96	1.01	1.06
	0.97	1.00	1.01	1.02	0.98
Nonlinear hedging					
5	1.29	1.29	1.29	1.29	1.29
	0.06	0.12	0.18	0.23	0.28
	0.07	0.03	−0.02	−0.10	−0.20
10	1.28	1.29	1.29	1.28	1.29
	0.17	0.30	0.42	0.52	0.60
	0.28	0.26	0.19	0.05	−0.33
15	1.29	1.29	1.29	1.29	1.29
	0.30	0.49	0.69	0.86	1.00
	0.54	0.56	0.55	0.50	0.07
20	1.29	1.29	1.29	1.28	1.29
	0.41	0.69	0.93	1.15	1.37
	0.75	0.82	0.90	0.97	1.05
25	1.29	1.29	1.29	1.29	1.28
	0.51	0.82	1.09	1.37	1.55
	0.90	1.01	1.10	1.22	1.37
30	1.29	1.29	1.29	1.28	1.29
	0.60	0.95	1.24	1.50	1.72
	1.00	1.12	1.21	1.30	1.30

Note: The weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, $p = 0.7$, and $\sigma_{t_e} = 20$. All estimates are computed using 20,000 simulation runs. In each cell representing a combination of correlation coefficient and standard deviation of the local weather index, the hedge ratio values are listed vertically downward in the order h_{l-ll}, h_{e-lb}, and h_{d-lb}, respectively, for linear hedging; and h_{l-nl}, h_{e-nb}, and h_{d-nb}, respectively, for nonlinear hedging.

The OTC basis forward is intended to be used to complement the weather future contract. The intuition concerning the impact of credit risk on the use of the basis forward is that, with increase of credit risk, the basis forward contract loses its balance between its two component options (a put option and a call option), and hence loses its ability to properly align with the weather future contract. Because the basis forward is losing its complementary function, it will be used less with an increase in credit risk. After credit risk passes a turning point, the basis forward loses its complementary function completely. As the credit risk gets higher, the basis forward will go its own way and be used to earn more premiums (instead of complementing the weather future contract), just like the use of the local weather forward. The complementary part of the weather future, on the other hand is lost partly or completely with increase of credit risk, and consequently will be used less.

Concerning the impact of basis risk, it is pretty obvious (see Ederington, 1979; Haushalter, 2000) that the exchange traded weather future will be used more with decreases in basis risk. The more interesting finding concerns the use of the basis forward contract. At high levels of basis risk, the basis forward contract will also be used more with decrease of basis risk to match the weather future contract. However, as basis risk gets lower and lower (the correlation between firm value and the value of the exchange traded weather contract gets higher and higher), the weather future does not need to be complemented as much, and hence at low basis risk levels the basis forward will be used less with decreases of basis risk.

For nonlinear local hedging using OTC local weather put options, the simulation results indicate that the hedge ratio h_{l-nl} (*nl* denotes "nonlinear local hedging") on the OTC local weather put option decreases in credit risk, and this hedge ratio converges to 1 as credit risk approaches 1. The impact of credit risk here is fairly clear. With an increase in credit risk, the OTC local weather put option will not be as attractive to the hedger, and will be used less. Similar to what was seen with linear local hedging using OTC local forwards, the standard deviation of the local weather index has no impact on the use of the OTC local put option. This reflects that nonlinear local hedging using OTC local put options is just a perfect nonlinear hedge "discounted" by credit risk, and given the credit risk level, the hedge ratio on the OTC local put option is always the same regardless of the weather risk itself.

For nonlinear basis hedging using both exchange traded put options and OTC basis put options, the simulation results indicate that the hedge ratio h_{e-nb} (*nb* denotes "nonlinear basis hedging") on the exchange traded weather put options decreases in credit risk at high levels of weather risk. This hedge ratio decreases in basis risk, and it is more sensitive to basis risk when weather risk is at high levels. Generally, this hedge ratio is very sensitive to weather risk and basis risk.

The hedge ratio h_{d-nb} on the OTC basis weather put option decreases in credit risk. This hedge ratio is concave in basis risk, initially increasing and then decreasing. The hedge ratio on the exchanged traded put option and the hedge ratio on the OTC basis put option both increase in the standard deviation of the local index, in order to hedge more of the weather risk.

Intuitively, similar to what was observed with the OTC local weather put option, the OTC basis put option will be used less with increases in credit risk. The exchange traded put option will also be used less with increases in credit risk because the option is losing its complementary part (the OTC basis put option is intended to complement the exchange traded put option) and cannot function as well alone.

At high basis risk levels the exchange traded put option will be used more with decreases in basis risk. To complement this exchange traded contract, the OTC basis put option will also be used more with decreases in basis risk. However, at low basis risk levels, the exchange traded weather put option does not need to be complemented very much anymore, and to reduce credit risk, the OTC basis put option will be used less with decreases of basis risk.

BASIS HEDGING EFFECTIVENESS

Having solved for the optimal hedge ratios, it is important to know whether basis hedging strategy using both exchange traded weather contracts and OTC basis contracts is effective compared to local hedging strategies using OTC local weather contracts. In this section, we present the results of a series of simulations used to examine the impact of weather risk, basis risk, and credit risk on hedging effectiveness. As before, credit risk is represented by $1 - p$, weather risk is represented by the standard deviation of the local index (σ_{t_l}), and basis risk is characterized by the correlation between local weather index and the exchange-listed standard weather index (ρ_{t_l,t_e}). We also assume weather indices are normally distributed, and the hedging objective is variance minimization (the optimal hedging problem is $\mathrm{MIN}_h\ \sigma^2\ (W\,|\,\theta)$), which is the same as mean-variance objective ($\mathrm{MAX}_h\, E(W\,|\,\theta) - \lambda\ \sigma^2\ (W\,|\,\theta)$) in the unbiased market.

Under the assumption that quantity risk is linear in local weather index, $q = \alpha + \beta t_l + \varepsilon$, the minimum variances of linear local hedging using OTC local forwards and linear basis hedging using both exchange traded futures and OTC basis forwards are

$$\begin{aligned} V_{\min-ll} = {} & \beta^2\sigma_{t_l}^2 + \sigma_\varepsilon^2 + h_{l-ll}^{*2}\, p\sigma_{r_l^p}^2 + h_{l-ll}^{*2}\sigma_{r_l^c}^2 + h_{l-ll}^{*2}(p - p^2)\mu_{r_l^p}^2 \\ & - 2ph_{l-ll}^{*2}\sigma_{r_l^p,r_l^c} + 2h_{l-ll}^{*}\beta p\sigma_{t_l,r_l^p} - 2h_{l-ll}^{*}\beta\sigma_{t_l,t_l^c} \end{aligned} \tag{20}$$

and

$$\begin{aligned} V_{\min-lb} = {} & \beta^2\sigma_{t_l}^2 + \sigma_\varepsilon^2 + h_{e-lb}^{*2}\sigma_{t_e}^2 + h_{d-lb}^{*2}\, p\sigma_{r_d^p}^2 + h_{d-lb}^{*2}\sigma_{r_d^c}^2 \\ & + h_{d-lb}^{*2}(p - p^2)\mu_{r_d^p}^2 - 2ph_{d-lb}^{*2}\sigma_{r_d^p,r_d^c} - 2h_{e-lb}^{*}\beta\sigma_{t_l,t_e} + 2h_{d-lb}^{*}\beta p\sigma_{t_l,r_d^p} \\ & - 2h_{d-lb}^{*}\beta\sigma_{t_l,r_d^c} - 2h_{e-lb}^{*}h_{d-lb}^{*}\, p\sigma_{t_e,r_d^p} + 2h_{e-lb}^{*}h_{d-lb}^{*}\sigma_{t_e,r_d^c}. \end{aligned} \tag{21}$$

The hedging effectiveness of linear basis hedging using both exchange traded futures and OTC basis forwards is measured by

$$HE_{lb} = \frac{V_{\min-ll} - V_{\min-lb}}{V_{\min-ll}}. \tag{22}$$

Under the assumption that quantity risk is linear in local weather index, the minimum variances of nonlinear local hedging using OTC local weather put options and nonlinear basis hedging using both exchange traded put options and OTC basis put options are

$$V_{\min-nl} = \beta^2\sigma_{t_l}^2 + \sigma_\varepsilon^2 + h_{l-nl}^{*2} p\sigma_{r_l^p}^2 + h_{l-nl}^{*2}(p - p^2)\mu_{r_l^p}^2 + 2h_{l-nl}^{*}\beta p\sigma_{t_l,r_l^p} \tag{23}$$

and

$$\begin{aligned} V_{\min-nb} = {} & \beta^2\sigma_{t_l}^2 + \sigma_\varepsilon^2 + h_{e-nb}^{*2}\sigma_{r_e^p}^2 + h_{d-nb}^{*2} p\sigma_{r_d^p}^2 + h_{d-nb}^{*2}(p - p^2)\mu_{r_d^p}^2 \\ & + 2h_{e-nb}^{*}\beta\sigma_{t_l,r_e^p} + 2h_{d-nb}^{*}\beta p\sigma_{t_l,r_d^p} + 2h_{e-nb}^{*}h_{d-nb}^{*} p\sigma_{r_e^p,r_d^p}. \end{aligned} \tag{24}$$

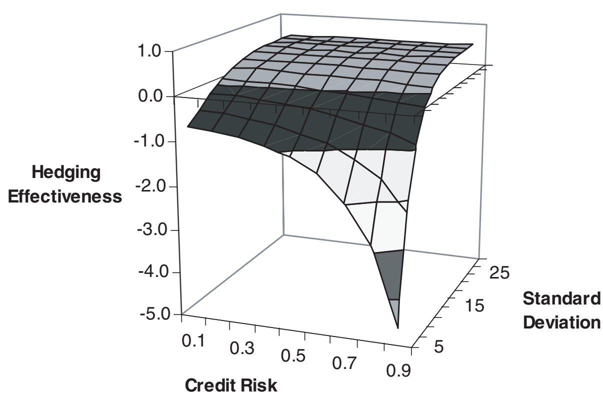
Similarly, the hedging effectiveness of nonlinear basis hedging using both exchange traded put options and OTC basis put options is measured by

$$HE_{nb} = \frac{V_{\min-nl} - V_{\min-nb}}{V_{\min-nl}}. \tag{25}$$

Basis hedging effectiveness is inversely related to σ_ε^2. For the simulation results presented we assume that $\sigma_\varepsilon^2 = 0$ and $\beta = 1$. We also assume that the strike levels satisfy $T_l = \mu_{t_l}$, $T_e = \mu_{t_e}$, and $T_d = \mu_{t_d}$. The hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations described in the section "Basis Hedging Behavior."

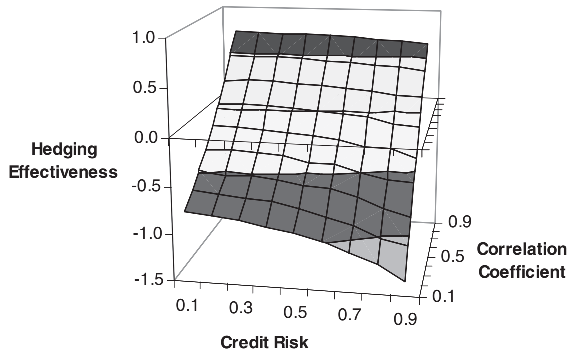
Figures 1–3 illustrate the hedging effectiveness of linear basis hedging strategy using both exchange traded futures and OTC basis forwards under different levels of credit risk $(1 - p)$, the standard deviation of the local weather index, and the correlation

FIGURE 1
Linear Basis Hedging Effectiveness Under Different Levels of p and σ_{t_l}



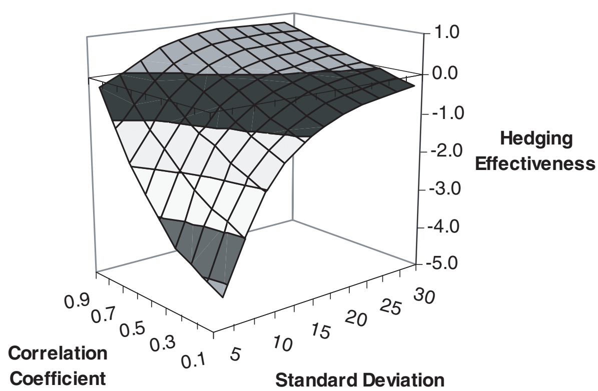
Note: Weather indices t_l and t_e are bivariate normally distributed. $\rho_{t_e,t_l} = 0.7$, $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, and $\sigma_{t_e} = 20$. The basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

FIGURE 2
Linear Basis Hedging Effectiveness Under Different Levels of p and ρ_{t_l,t_e}



Note: Weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, $\sigma_{t_l} = 15$, and $\sigma_{t_e} = 20$. The basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

FIGURE 3
Linear Basis Hedging Effectiveness Under Different Levels of σ_{t_l} and ρ_{t_l,t_e}



Note: Weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, $p = 0.7$, and $\sigma_{t_e} = 20$. The basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

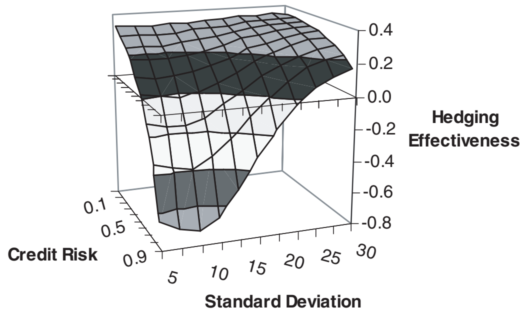
between the local index and the exchange-listed index. From these figures we observe that linear basis hedging using both exchange traded futures and OTC basis forwards is much effective when basis risk is low (the correlation between firm value and the value of the exchange traded weather contract is high) and weather risk is high (firm value has a high sensitivity to weather conditions). Generally, credit risk does not have much of an impact on linear hedging effectiveness when weather risk is not too low (the sensitivity of firm value to weather conditions is not too low) and basis risk is not too high (the correlation between firm value and the value of the exchange traded weather contract is not too low).

From these figures we also observe that linear basis hedging effectiveness increases in weather risk. The sensitivity of the linear basis hedging effectiveness to weather risk is greater when credit risk is low and basis risk is high (the correlation between firm value and the value of the exchange traded weather contract is low). We observe that when weather risk is high (firm value has a high sensitivity to weather conditions), linear basis hedging effectiveness is fairly constant. Moreover, linear basis hedging effectiveness decreases in basis risk. The sensitivity of linear basis hedging effectiveness to basis risk is almost the same at all levels of credit risk, however this sensitivity is greater when weather risk is low (firm value has a low sensitivity to weather conditions), while it is almost constant when weather risk is high (firm value has a high sensitivity to weather conditions). The intuition is that either a lower basis risk or a higher weather risk implies more variance reduction for linear basis hedging strategy using both exchange traded futures and OTC basis forwards than for linear local hedging strategy using OTC local weather forwards.

From the figures we see that linear basis hedging effectiveness appears to increase in credit risk when weather risk is low (firm value has a low sensitivity to weather conditions) and basis risk is high (the correlation between changes in the value of the exchange traded weather contract and changes in firm value is low). This reflects that when weather risk is low (firm value has a low sensitivity to weather conditions) and basis risk is high (the correlation between changes in the value of the exchange traded weather contract and changes in firm value is low), a higher credit risk implies more of an increase in variance for linear local hedging strategy using OTC local weather forwards than it does for a linear basis hedging strategy using both exchange traded futures and OTC basis forwards. In the situation (which is most probably more often the case in the real world) when basis risk is not too high (the correlation between the value of the exchange traded weather contract and firm value is not too low) and weather risk is not too low (the sensitivity of firm value to weather conditions is not too low), linear basis hedging using both exchange traded futures and OTC basis forwards is more effective than linear local hedging using OTC local weather forwards. It is interesting to note, however, in this same situation credit risk has no apparent impact on linear basis hedging effectiveness. This reflects that a higher credit risk does not imply a more significant variance increase with either linear local hedging strategy using OTC local forwards or linear basis hedging strategy using both exchange traded futures and OTC basis forwards when weather risk is not too low (the sensitivity of firm value to weather conditions is not too low) and basis risk is not too high (the correlation between the value of the exchange traded weather contract and firm value is not too low).

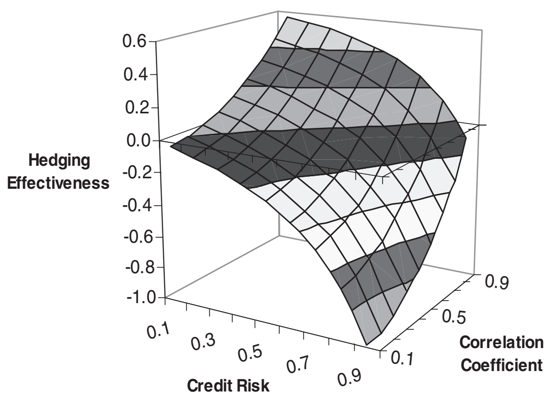
Figures 4–6 illustrate the hedging effectiveness of employing a nonlinear basis hedging strategy using both exchange traded weather put options and OTC basis put options under different levels of credit risk $(1 - p)$, the standard deviation of the local weather index, and the correlation between the local index and the exchange-listed index. Similar to the results obtained for linear basis hedging strategy using both exchange traded futures and OTC basis forwards, nonlinear basis hedging using exchange traded put options and OTC basis put options is much effective when basis risk is low (the correlation between firm value and the value of the exchange traded contract is high) and weather risk is high (the sensitivity of firm value to weather

FIGURE 4
Nonlinear Basis Hedging Effectiveness Under Different Levels of p and σ_{t_l}



Note: Weather indices t_l and t_e are bivariate normally distributed. $\rho_{t_e,t_l} = 0.7$, $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, and $\sigma_{t_e} = 20$. The basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

FIGURE 5
Nonlinear Basis Hedging Effectiveness Under Different Levels of p and ρ_{t_l,t_e}



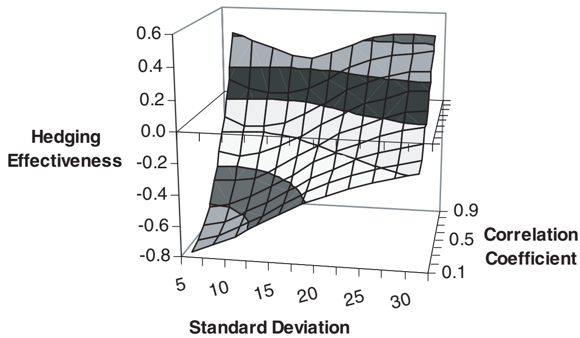
Note: Weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, $\sigma_{t_l} = 15$, and $\sigma_{t_e} = 20$. the basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

conditions is high). Contrasting with results from linear basis hedging strategy using exchange traded futures and OTC basis forwards, however, credit risk plays a significant role in nonlinear basis hedging effectiveness.

The simulation results also indicate that nonlinear basis hedging effectiveness decreases in basis risk. The sensitivity to basis risk of the effectiveness of employing nonlinear basis hedging using both exchange traded put options and OTC basis put options is greater when credit risk is high and weather risk is low (the sensitivity of firm value to weather conditions is low). Intuitively this is since a lower basis risk implies a greater variance reduction for nonlinear basis hedging strategy using both exchange traded put options and OTC basis put options than for nonlinear local hedging strategy using OTC local put options.

FIGURE 6

Nonlinear Basis Hedging Effectiveness Under Different Levels of σ_{t_l} and ρ_{t_l,t_e}



Note: Weather indices t_l and t_e are bivariate normally distributed. $T_e = \mu_{t_e} = 100$, $T_l = \mu_{t_l} = 80$, $T_d = \mu_{t_l - t_e} = -20$, $p = 0.7$, and $\sigma_{t_e} = 20$. The basis hedging effectiveness is computed from the random samples of (t_e, t_l) generated from the corresponding simulations in the section "Basis Hedging Behavior."

Generally, nonlinear basis hedging effectiveness is convex in weather risk, initially decreasing and then increasing. The effectiveness sensitivity of nonlinear basis hedging using both exchange traded put options and OTC basis put options to changes in weather risk is greater when credit risk is low; however, it is not very sensitive at all when credit risk is very high. The degree of convexity in nonlinear basis hedging effectiveness is much higher when basis risk is low (the correlation between firm value and the value of the exchange traded weather contract is high), whereas when basis risk is at high levels it is not so obviously convex. This reflects that, generally, at high levels of weather risk more variance reduction is obtained by using a nonlinear basis hedging strategy with both exchange traded put options and OTC basis put options than by using a nonlinear local hedging strategy with OTC local put options. By contrast, at low levels of weather risk there is more variance reduction utilizing a nonlinear local hedging strategy with OTC local put options than for nonlinear basis hedging strategy with both exchange traded put options and OTC basis put options.

The simulation results also indicate that nonlinear basis hedging effectiveness increases in credit risk. The sensitivity of nonlinear basis hedging effectiveness to credit risk is greater when weather risk is low (the sensitivity of firm value to weather conditions is low) and basis risk is high (the correlation between firm value and the value of the exchange traded weather contract is low). The intuition for this result is that a higher credit risk implies a greater variance increase when using a nonlinear local hedging strategy with OTC local put options than when using a nonlinear basis hedging strategy with both exchange traded put options and OTC basis put options. A possible explanation is that, with an increase in credit risk, the OTC local put option becomes less attractive while the variance of nonlinear local hedging using OTC local put options increases because less of this put option is used. On the other hand, since the basis put option only plays a complementary role in this setting, the variance in using the nonlinear basis hedging strategy with both exchange traded put options and OTC basis put options does not increase as much as the variance involved in using the nonlinear local hedging strategy with OTC local put options.

CONCLUSION

Weather derivatives constitute a rather recent addition to the collection of financial products designed to help firms hedge against weather related risks. Given the infinite diversity of weather locations and the finite number of contracts that any exchange can trade, market users will face basis risk unless their particular exposure location happens to coincide with an exchange traded weather contract centered at the firm's exposure location. The use of OTC contracts can be tailored to be so centered at the firm's exposure location; however, in such contracts counterparty default risk occurs.

This article analyzes the risk sharing efficiency effects due to the joint use of the standardized exchange traded weather derivatives and some OTC weather derivatives for hedging basis risk, with consideration of hedgeable basis risk and nonhedgeable credit risk. Simulations are conducted to illustrate the determinants of hedge ratios and hedging effectiveness. Simulation results indicate that linear and nonlinear basis hedging strategies using both exchange traded weather contracts and OTC basis weather contracts are much effective when basis risk is low (the correlation between firm value and the value of the exchange traded weather contract is high) and weather risk is high (the sensitivity of firm value to weather conditions is high). Generally, credit risk does not have much impact on linear basis hedging effectiveness when weather risk is not too low (the sensitivity of firm value to weather conditions is not too low) and basis risk is not too high (the correlation between firm value and the value of the exchange traded weather contract is not too low), while nonlinear basis hedging effectiveness increases significantly in credit risk unless weather risk is very high (the sensitivity of firm value to weather conditions is very high).

As for future work, the basis hedging problem is tackled in this article using a mean-variance framework. An interesting extension of this work would be to examine the efficiency gains of basis hedging using other objective functions. Furthermore, in this work we have simplified the model by analyzing quantity risk only. An important task for future research is to generalize this analysis by including both quantity risk and price risk in the weather hedging model. In addition, we have simplified the model by considering a two-date economy and one might adapt the framework to multiperiod and continuous cases.

APPENDIX

Under the assumption that the demand quantity q is linearly related to the weather temperature index t_l, i.e., $q = \alpha + \beta t_l + \varepsilon$, the optimal linear local hedge ratio can be restated as

$$h^*_{l-ll} = \frac{-p\beta\sigma_{t_l,r_l^p} + \beta\sigma_{t_l,r_l^c}}{p\sigma^2_{r_l^p} + \sigma^2_{r_l^c} + (p-p^2)\mu^2_{r_l^p} - 2p\sigma_{r_l^p,r_l^c}}. \tag{A1}$$

Similarly, the optimal linear basis hedge ratios can be restated as

$$h^*_{d-lb} = \frac{\beta\sigma_{t_l,t_e}\left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right) + \beta\sigma^2_{t_e}\left(\sigma_{t_l,r_d^c} - p\sigma_{t_l,r_d^p}\right)}{\sigma^2_{t_e}\left[p\sigma^2_{r_d^p} + (p-p^2)\mu^2_{r_d^p} + \sigma^2_{r_d^c} - 2p\sigma_{r_d^p,r_d^c}\right] - \left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)^2} \tag{A2}$$

and

$$h^*_{e-lb} = \frac{\beta\left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)\left(\sigma_{t_l,r_d^c} - p\sigma_{t_l,r_d^p}\right) + \beta\sigma_{t_l,t_e}\left[p\sigma^2_{r_d^p} + \sigma^2_{r_d^c} + (p-p^2)\mu^2_{r_d^p} - 2p\sigma_{r_d^p,r_d^c}\right]}{\sigma^2_{t_e}\left[p\sigma^2_{r_d^p} + (p-p^2)\mu^2_{r_d^p} + \sigma^2_{r_d^c} - 2p\sigma_{r_d^p,r_d^c}\right] - \left(p\sigma_{t_e,r_d^p} - \sigma_{t_e,r_d^c}\right)^2}. \tag{A3}$$

In addition, the optimal nonlinear local hedge ratio is

$$h^*_{l-nl} = \frac{-\beta\sigma_{t_l,r_l^p}}{\sigma^2_{r_l^p} + (1-p)\mu^2_{r_l^p}} \tag{A4}$$

and the optimal nonlinear basis hedge ratios are

$$h^*_{d-nb} = \frac{\beta\sigma_{t_l,r_e^p}\sigma_{r_e^p,r_d^p} - \beta\sigma_{t_l,r_d^p}\sigma^2_{r_e^p}}{\sigma^2_{r_e^p}\sigma^2_{r_d^p}\left(1 - p\rho^2_{r_e^p,r_d^p}\right) + (1-p)\sigma^2_{r_e^p}\mu^2_{r_d^p}} \tag{A5}$$

and

$$h^*_{e-nb} = \frac{(p-1)\beta\mu^2_{r_d^p}\sigma_{t_l,r_e^p} + p\beta\sigma_{t_l,r_d^p}\sigma_{r_e^p,r_d^p} - \beta\sigma_{t_l,r_e^p}\sigma^2_{r_d^p}}{\sigma^2_{r_e^p}\sigma^2_{r_d^p}\left(1 - p\rho^2_{r_e^p,r_d^p}\right) + (1-p)\sigma^2_{r_e^p}\mu^2_{r_d^p}}. \tag{A6}$$

Here *ll* denotes "linear local hedging," *lb* denotes "linear basis hedging," *nl* denotes "nonlinear local hedging," and *nb* denotes "nonlinear basis hedging."

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