

Introduction to Weather Derivative Pricing

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Over the last seven years weather derivatives have emerged as an attractive new asset class, uncorrelated with almost all other kinds of investment, and a number of insurance companies, reinsurance companies, banks, hedge funds, and energy companies have set up weather trading desks. The weather derivative portfolios they hold might contain a few hundred contracts, and contract sizes (in terms of the maximum payout) typically range from a few hundred thousand to tens of millions of U.S. dollars.

Trading strategies vary from company to company, and weather derivatives can be used to create profitable investment portfolios in a number of ways. For example:

- A diversified portfolio of weather derivatives can give good return for very low risk because of the many different and uncorrelated weather indices on which weather derivatives are based.
- A portfolio of weather derivative and commodity trades can be high return but low risk because of the correlations between weather and commodity prices.
- A portfolio of more standard investments (such as stocks and bonds) that contains a small number of weather derivatives can give a lower risk than a portfolio of standard investments alone because of the lack of correlation between the weather derivatives and the wider financial markets.

For those who trade and invest in weather derivatives the methods used for pricing and risk management are very important and this article gives an overview of the pricing and risk management methods that are used in industry. Also at the end of the article we briefly mention some pricing methods that have been suggested in the academic literature.

We start with the simplest case which is the pricing of weather swaps. We then discuss the pricing of weather options, and argue that both actuarial and arbitrage pricing can be relevant. We describe briefly the most important aspects of portfolio modeling and risk management. Finally we mention some other important topics such as daily modeling of temperature and seasonal forecasts.

PRICING OF WEATHER SWAPS

We start our discussion of the pricing of weather derivatives with the simplest case, which is the pricing of weather swaps. Such contracts are, technically speaking, either forward or future contracts. They are traded without a premium and have a payoff that is linearly dependent on some weather index. Prices are quoted in terms of the strike level of the index. Swaps as forwards (which are mostly capped, and so are not strictly linear) are traded OTC for a very wide range of locations and indices. Swaps as futures (which don't have caps) are traded on the Chicago Mercantile Exchange for monthly and seasonal

contracts on 21 locations: 15 in the U.S., 5 in Europe, and 1 in Japan. All the exchange traded swaps are based on daily temperatures, but the daily temperatures are converted into the monthly or seasonal settlement index in different ways in different regions. In the U.S., daily winter temperatures are first converted into daily heating degree days (a measure of cold based on the size of temperature excursions below a baseline) and daily summer temperatures are converted into daily cooling degree days (a measure of heat based on the size of temperature excursions above a baseline). Both heating and cooling degree days are then summed across the period of the weather contract to create the settlement index. In Europe, daily winter temperatures are converted into heating degree days in the same way while daily summer temperatures are summed across the period of the contract directly. In Japan the monthly or seasonal index is formed as the average temperature across the period of the contract.

Actuarial Pricing

How should swap contracts be priced, i.e., how should the strike level be determined? We first consider actuarial pricing. For many OTC weather contracts this is the only possible method for pricing since observable markets don't exist.

Actuarial pricing consists of considering appropriate historical meteorological data and meteorological forecasts and using this data to derive a prediction for the distribution of outcomes for the settlement index. The first stage of such an analysis is that the historical data has to be cleaned and corrected because of the presence of gaps (due to failures in measuring equipment and data transmission systems) and discontinuities (due to station changes): we don't discuss these cleaning and correction processes in detail, but refer the reader to Boissonnade et al. [2002].

Even after such cleaning and correction meteorological data is generally not stationary but contains trends due to climate change and the urbanization of weather stations over time. These effects mean that the weather over the last 50 years is not a good indication of the future weather and the distribution of likely settlement levels of a weather contract. This problem can be tackled in two ways: either one can use only a short period of recent data, such as 10 years, and assume that over this short period the non-stationarity is small enough to ignore, or one can use a longer period of data, such as 30 or 50 years, and attempt to model the trend. Both these methods are commonly used in practice: the former has the advantage

that it is simple, but the predictions it gives are biased (because of the trend) and estimates of probabilities in the tail of the distribution are very poor. The latter method has the advantage that the bias is lower and the tails of the distribution are better estimated but the disadvantage that the variance of errors is typically greater because of parameter uncertainty on the parameters in the trend model. These issues, along with some empirical comparisons of different detrending methods applied to U.S. temperature data, are described in detail in Jewson and Brix [2004] and Jewson [2004h].

The main goal of actuarial pricing for swaps is to establish the expectation of the settlement index, which is often called the fair strike. If a contract is traded many times at the fair strike then neither party will win or lose on average. One can estimate this fair strike simply as the average of the (possibly detrended) historical values for the settlement index. Because of the trends and the limited number of years of data there is significant uncertainty about these estimates: simple methods for estimating the size of pricing uncertainty for both swaps and options are given in Jewson [2003f].

Market Pricing

We now consider cases in which there is an observable market for the weather swap. For certain locations, particularly London, Chicago, and New York, one might consider that the weather swap market trades frequently enough (currently several trades per day) that this market is likely to be reasonably efficient as a mechanism for fair strike discovery. For valuation of currently held positions these market strikes can then be used instead of results of an actuarial analysis. One can also compare these market prices with the results of actuarial analysis: in most cases one finds that the market prices lie within the range of possible values given by the actuarial analysis and only occasionally do the prices for commonly traded contracts move out of this range, presumably because of supply and demand imbalance.

As a weather swap contract progresses toward expiry, market price inevitably converges onto fundamental price and the two are equal at expiry.

The Role of Forecasts

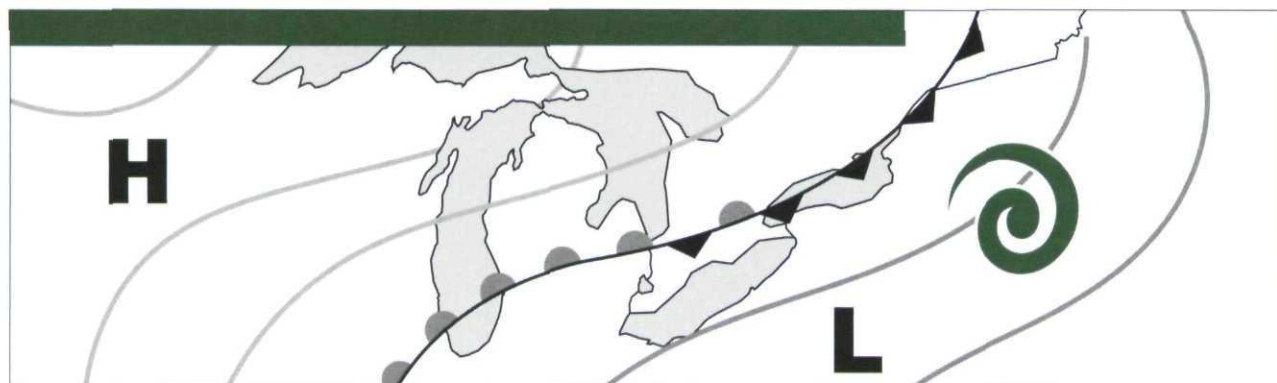
Immediately before and during the measurement period for a swap contract weather forecasts play an important role in helping predict the likely outcome of the con-

tract, and the movements in the prices of commonly traded contracts are almost entirely driven by changes in weather forecasts. Weather forecasts can be incorporated into estimates of the fair strike of most weather swap contracts in a very simple fashion. The starting point is to ensure that the forecast being used represents the expectation of future temperatures. This is not always the case for commercially available forecasts and methods to ensure that a particular weather forecast really does represent an expectation are given in Jewson [2002]. Then, for a contract based on the sum of temperatures over the contract period, or a contract on degree days for which there is no chance of crossing the baseline, the results from the weather forecast can simply be added to an actuarial analysis for the remainder of the contract. Other cases, such as contracts based on degree days in situations where there is some chance of the temperature crossing the baseline, are more complex and should be priced using probabilistic forecasts of future temperatures. Methods for making such forecasts from the single and ensemble meteorological forecasts available commercially are discussed in Jewson [2004c]. How probabilistic forecasts should be used in pricing is discussed in Jewson and Caballero [2003b].

PRICING OF WEATHER OPTIONS

We now move on to discuss the pricing of weather options, which are contracts with a non-linear rather than linear payoff, and which are exchanged for a premium. The first case we consider is that of a weather option on a location for which there is no weather swap market. This would be the case for most OTC weather options structured for end users with weather risk. In this case the only pricing method available is to perform an actuarial analysis based on historical meteorological data. The analysis is slightly more complicated than that for swap contracts since one is now interested in the distribution of possible values for the settlement index, rather than just the expected value. The concept of primary interest is the expected payoff of the option (with expectations calculated under the objective measure), and this is often referred to as the fair price of the option. An option contract traded many times with the premium set at this fair price will neither make nor lose money on average.

The simplest way to estimate this expected payoff uses so-called burn analysis in which we calculate how the option would have performed in previous years. A slightly more complex approach involves fitting a distribution to



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the historical index values and calculating the expected payoff from this distribution. Both of these methods have been in use since the beginnings of the weather market, although the earliest reference we have been able to find is Goldman Sachs [1999]. Fitting a distribution may possibly give slightly more accurate estimates of the fair premium in some cases, and may well give more accurate estimates of the greeks and the risk of extreme events (see Jewson [2003e] for a quantitative comparison between the burn and index modeling approaches). In the case of the normal and kernel distributions, a number of closed-form expressions have been published (see McIntyre [1999] and Henderson [2002] for individual examples, and Jewson [2003a, 2003b, 2003d] for a comprehensive list of results for all common contract types). Normal distributions are generally appropriate for seasonal contracts, but not necessarily for standard monthly contracts, and certainly not for exotic contracts based on the number of extreme weather events such as the number of freezing days over winter. In Jewson [2004f] we give an analysis of the effectiveness of the normal distribution for seasonal and monthly indices based on U.S. temperatures. For distributions other than the normal or kernel closed-form solutions may also be possible, and for all distributions Monte Carlo simulations or numerical integration can be used to calculate the fair price and other diagnostics.

The amount of historical data available does not pin down the distribution of the settlement index very precisely, and there are often several distributions that cannot be rejected using statistical testing. For options with strikes near the mean and when calculating the expected payoff one can choose any of these distributions for pricing since the choice of distribution does not have a major effect on the results: the choice of number of years or trend is much more important. For options with strikes far from the mean, the choice of distribution becomes more important, however (see Jewson [2004e] for a detailed comparison of the relative importance of trends and distributions).

Having calculated the expected payoff of an option, the seller may wish to add a premium to compensate for the unhedgeable risk being taken on. Such a premium would usually be calculated to be proportional to some measure of risk; e.g., one might add 30% of the standard deviation of the payoffs. Closed-form expressions for the standard deviation of the payoffs of options on normal and kernel distributions are given in Jewson [2003c]. The standard deviation of payoffs for other distributions can be calculated using Monte Carlo methods.

Use of Weather Forecasts

The use of weather forecasts in the pricing of weather options is more complex than for the case of swaps. For illustration we consider a case in which the index distribution is normal and is hence entirely specified by the mean and the standard deviation. The mean can be calculated easily as for swaps, but the calculation of the standard deviation is difficult. In Jewson and Caballero [2003b] we describe three rather different methods that can be used to estimate the standard deviation:

- a simple but rather approximate method based on historical meteorological data;
- a very complex bottom-up approach based on probabilistic forecasts of temperature and daily temperature simulation models (which we call “pruning”); and
- a straightforward approach based on the use of Brownian motion to model the expected index.

The third approach involves specifying a volatility model for the expected index. As an example of such a model, the seasonal trapezium volatility model that we describe in Jewson [2003h] captures both the overlapping effects of weather forecasts at the start and ends of a contract and also the varying volatility of weather at different times of year.

Market Based Pricing of Weather Options

We now consider the pricing of weather options in the case in which there is a liquid market for the weather swap. In this case one can consider hedging the option using the swap, and under the simplest set of assumptions (that the market is balanced and the swap price is equal to the expected settlement index) the resulting model is a modified version of the Black [1976] model for pricing options on forwards (see Jewson and Zervos [2003a]). In the Black model the underlying process is given by a geometric Brownian motion with drift while for the weather swap it is more appropriate to use an arithmetic Brownian motion with no drift (see Jewson [2002] for a detailed explanation of this). The arbitrage price one derives from this model is identical to the actuarially derived fair price and the risk neutral measure is the same as the natural measure, unlike in the Black and Black-Scholes models. The basic weather version of the Black model can also be extended by including a drift in the swap price to repre-

sent an unbalanced market (see Jewson and Zervos [2003b]). In this case the arbitrage price is no longer exactly the actuarial fair price.

In reality, weather swap markets are not particularly liquid and the above models are not particularly well justified, depending as they do on assumptions of infinite liquidity and zero transaction costs.

However, some hedging of options with swaps is certainly possible. The optimum number of hedges depends on the liquidity of the swap market, the level of transaction costs, and the risk aversion of the trader. We have explored a simple model of these effects, and the option prices that result, in Jewson [2003i].

When pricing options on an index for which the swap is commonly traded it is common practice to use the swap level instead of an actuarial estimate for the expected index. This can be considered as 1) actuarial pricing, with the assumption that the swap is a good predictor for the expected index, or 2) arbitrage pricing, where one is planning to continuously hedge the option with the swap, or 3) an approximation to the adjustment one should make to the option price to take into account the cost of hedging with just one single swap transaction.

PORTFOLIO MANAGEMENT

The lack of correlation between different weather variables, weather at different times, and weather in different parts of the world allows the creation of very low risk portfolios of weather contracts, and there is considerable interest from market makers in trying to originate a wide variety of different trades for this reason.

Modeling a portfolio to estimate the distribution of possible outcomes can be performed by fitting marginal distributions to each contract, estimating rank correlations between the indices, and simulating using the well-known simulation method of Iman and Conover [1982]. The application of this model to weather derivatives was first described by Jewson and Brix [2000] but may have been in use in the weather derivative industry before then.

There are a number of aspects to the management of a weather portfolio, such as:

1. Identifying and hedging the major sources of risk in the current portfolio: A simple way to reduce the risk in a portfolio is to hedge using the liquidly traded swap contracts. The optimum (variance minimizing) size of the hedge is given by (minus one times) the regression coefficient (or beta) between the payoffs of the portfolio and the index of the swap.

This can be calculated either using simulations or, for the normal distribution at least, analytically (see Jewson [2004a]). Since the more liquidly traded swap contracts can be traded at or close to fair price it may make sense to attempt beta neutrality with respect to these indices with fairly frequent reheding.

Other definitions of optimum other than variance minimizing can also be considered, and lead to different sizes of hedge (see Jewson [2004b]).

2. Pricing against the portfolio: If one cares about both risk and return then all new contracts should ideally be priced in a way that reflects the impact they will have on both the risk and return of the portfolio. There are a number of frameworks that can be used for this such as traditional mean-variance analysis (see Markowitz [1959]), risk-adjusted return analysis (such as Sharpe ratio based analysis), or stochastic dominance theory (see Heyer [2001]). From an academic perspective one might also consider utility theory, but this does not seem to be used in practice.

RISK MANAGEMENT

There are a number of sources of risk in a weather portfolio. The most fundamental is the weather itself: a typical portfolio will have a range of possible outcomes that depends on the weather, and if the weather moves against the trader the trader can lose money. This risk is typically measured in two ways. The first, and most useful, is the so-called expiry VaR in which one considers holding all the contracts to expiry and calculating the lower quantiles of the distribution of profit and loss. These quantities can be estimated using the simulation methods for portfolios that have been described above. The second is the so-called horizon VaR, which is more similar to the standard definition of VaR since it measures the risk of loss over a specific time horizon. Horizon VaR for weather portfolios can be calculated on an actuarial basis or a market price basis. When considered on an actuarial basis horizon VaR is defined as one of the lower quantiles of the distribution of changes in the expected payoff from the portfolio over a fixed time horizon. There are a number of ways this can be calculated: a fully detailed calculation is extremely complex, but a simplified calculation based on the martingale nature of expected weather indices is much simpler (see Jewson [2003g]). When considered on a market basis horizon VaR is defined as the possible change in market value of a weather contract or portfolio of contracts over a specified time horizon. This

is generally very hard to estimate given the limited amount of weather market price data available.

If contracts are being traded in and out, rather than just held to expiry, then there is the potential of market risk: even if the weather is favorable, one may not be able to trade out of a contract at a reasonable price. Again this can be difficult to evaluate since it involves understanding the variations in liquidity in the market for which little data is available.

Other sources of risk that one may consider are liquidity risk (the risk that a portfolio that is performing well may suffer a short-term liquidity crisis because of the staggered timing of the payments from different contracts), and credit risk (the risk that a counterparty may go bankrupt).

FURTHER TOPICS

Daily Modeling

There has been considerable academic and some practitioner interest in the idea that actuarial pricing of weather options could be performed using simulation models for daily temperatures (see for instance Dischel [1998a], Cao and Wei [2000], Dornier and Querel [2000], Moreno [2000], Moreno and Roustant, [2002], Torro et al. [2001], Davis [2001], Alaton et al. [2002], Caballero et al. [2002], Brody et al. [2002], and Jewson and Caballero [2003a]).

Modeling daily temperatures could, in principle, lead to more accurate pricing, especially for short contracts (as shown in Jewson [2004g]), but is a difficult statistical problem. The difficulty arises because observed temperatures often show seasonality in all of the mean, variance, distribution, and autocorrelations, and long memory in the autocorrelations. The risk with daily modeling is that small mis-specifications in the models can lead to extreme mispricing of contracts. Many of the published articles on the subject, for instance, consider very simple models for daily temperature that give prices that are much less accurate than the more straightforward burn and index modeling methods described above. A typical problem is that daily models underestimate the autocorrelation of temperature fluctuations about the seasonal cycle and hence underestimate the standard deviation of the settlement index.

Seasonal Forecasts and El Niño

El Niño and La Niña have significant effects on the U.S. climate, and since they can be predicted a few months in advance it is important to consider their impact on the fair price of options and swaps (see Dischel [1998b] and Dischel [2000]). However, little work has been published on how to model the effects of El Niño on the distribution of temperatures at individual stations. Our own investigations into this subject are described in Jewson [2004d].

Other Variables

Our discussion thus far has focused entirely on temperature. However, a small but growing proportion of the weather market is based on precipitation, wind, and other variables. Most of the methods described above apply equally well to these other variables, with appropriate modifications. Discussions of the pricing of contracts based on precipitation have been given in Moreno [2001].

Pricing Weather-Commodity Dual Trigger Contracts

In addition to weather based contracts and commodity price based contracts a number of contracts with a dual strike based on weather *and* commodity prices have been traded in both the U.S. and Europe. The only article we know of that addresses the question of how to price such deals is Carmona and Villani [2003].

Alternative Pricing Paradigms

A number of alternative pricing paradigms for weather derivatives have been suggested in the academic literature. Examples are the use of CAPM-style equilibrium models (Cao and Wei [2000]) and using relations between the weather and gas or electricity prices (see Geman [1999a] and Davis [2001]). As far as the author is aware none of these ideas have been used in practice at this point.

CONCLUSIONS

We have reviewed the methods used by practitioners for the pricing of weather derivatives. In summary, weather derivative pricing is mostly based on an actuarial analysis of past weather data. Weather forecasts also play a role immediately before and during contracts, and seasonal forecasts are important in the U.S. For some of the more

liquidly traded contracts, especially monthly and seasonal temperature contracts on London, Chicago, and New York, enough of a market exists that swaps can be valued simply by observing the market price and one can attempt to value options using arbitrage pricing based models.

FURTHER READING

Good sources of articles on weather derivatives are the Artemis website at <http://www.artemis.bm> and the Social Science Research Network at <http://www.ssrn.org>. There are also several books that cover general aspects of the market and have short sections on pricing, written in English (Geman [1999b], Element Re [2002], and Dischel [2002]), Japanese (Hirose [2003], Hijikata [1999], and Hijikata [2003]), and French (Marteau et al. [2004]). The author has written a book that covers pricing issues in more detail (Jewson et al. [2004]).

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