Weather Derivatives: Instruments and Pricing Issues

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Introduction:

Since the summer of 1997, when the first weather derivatives transaction was recorded, we have witnessed the development of a new derivatives market in the United States, which is gradually expanding across the globe. The US Energy Department estimates that US$1 trillion of the US economy is exposed to weather risk. So far, the notional size of the weather derivatives traded is around US$3.5 billion, which represents a small amount compared with the size of the exposure.

The main players in the weather derivatives markets can be grouped in four main categories: Market Makers, Brokers, Insurance and Reinsurance Companies, and End-Users such as Gas and Power Marketers, Utilities and perhaps other market participants from retail, agriculture, travel, transport and distribution, leisure and tourism firms.

A derivative is a contract or security whose payoffs depend upon the price of some more fundamental, or "underlying" asset price. Derivatives are used to control the risks of naturally-arising exposures to such an asset price. For example, a gold miner might undertake the sales of gold future contracts (a derivative providing for the future exchange of money and gold) to diminish his natural exposures to the price of gold inherent in the ownership of the gold mine, i.e. its future gold production. In the weather case, the revenues of, for example, a ski slope operator, might reflect inherent weather risks which the operator may wish to mitigate via weather derivatives. For this purpose, the weather must be measured in some quantitative fashion, just like the price of gold.

Weather Measures

Just as an option on a commodity has as its underlying asset the price of a futures contract, a weather derivative has as its underlying "asset", a weather measure. The type of measure depends on the specifics of the contract. Most weather derivatives are based on Heating Degree Days (HDD) or Cooling Degree Days (CDD). Other contracts are based on precipitation, measured by the amount of rain over a given time period, or snowfall, measured by the amount of snow (including sleet) in a given period of time. However, it is estimated that 98-99% of the weather derivatives now traded are based on temperature.

HDD and CDD

Intuitively, HDD and CDD measure the heating and cooling demands that arise by departures of average daily temperatures from a base level.

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An HDD is the number of degrees by which the day's average temperature is below a base temperature, while a CDD is the number of degrees by which the day's average temperature is above a base temperature.

HDD and CDD are calculated as follows:

Daily HDD = Max (0, base temperature – daily average temperature)

Daily CDD = Max (0, daily average temperature – base temperature)

Base temperature is the pre-specified "base" temperature (usually 65 degrees Fahrenheit, but sometimes 75 in warmer climates). The *daily average temperature* is measured as the average between the daily high and daily low.

HDDs and CDDs are usually accumulated over a period of time. The most common derivative structures are based on the cumulative HDDs or CDDs for one month or one season (e.g. November to March). To calculate the HDD (CDD) over a period of days, we simply add up the daily HDD's (CDD's) for the period.

Calculation of Daily HDD and Cumulative HDD for a seven day period (HDD= Max (0, base temperature - daily average temperature)), where the base temperature is 65F.

WBAN #	Calculation of HDD (Base Temperature = 65 degrees Fahrenheit)							Total HDDs
Day	1	2	3	4	5	6	7	
Average Daily Temperature	50	48	55	67	61	51	49	
HDD	15	17	10	0	4	14	16	**76**

Calculation of Daily CDD and Cumulative CDD for a seven day period (CDD= Max (0, daily average temperature - base temperature)), where the base temperature is 65F.

WBAN #	Calculation of CDD (Base Temperature = 65 degrees Fahrenheit)							Total CDDs
Day	1	2	3	4	5	6	7	
Average Daily Temperature	76	66	64	60	68	70	74	
CDD	11	1	0	0	3	5	9	**29**

(Note: WBAN # denotes a particular geographic location where the temperature is observed.)

Occasionally other measures are used in weather derivatives: For example, Energy Degree Days are the sum of HDD or CDD for each day Growing Degree Days (GDDs) are used in agriculture, and are defined as the degrees between a certain range (e.g. between 55 and 75 degrees Fahrenheit).

Weather Derivatives Structures

The list of actual contracts in use is extensive and constantly evolving. Most of the weather derivatives traded up to date have been swaps and put or call options or combinations of these. In recent months, the weather derivatives market is starting to see customized structures for specific needs, such as binary or digital options, which either pay a fixed sum or zero depending on whether the payoff is satisfied, and double-trigger options, which pay off only if two conditions are met.

Payoffs are usually defined as a specified dollar amount (e.g. $1000 per degree day) multiplied by differences between the "strike" HDD (CDD) level specified in the contract and the actual cumulative HDD (CDD) level which occurred during the contract period.

In order to limit the maximum payout by any of the counterparties, the contracts are usually "capped," i.e. only a maximum amount of payout can change hands.

Call and Put Options

Weather derivatives typically have as their underlying "asset" either HDDs or CDDs.

However, since weather is not in fact a tradable asset, a dollar amount is associated with every degree day in the payoff calculation. For example, consider a CDD call option with a strike of 1000 CDD's paying $5000 per degree-day. The payoff for this option is:

$$Payoff\ Call = \$5000 \times Max\left(0, CDD_{t|T} - 1000\right)$$

where $CDD_{t|T}$ is the cumulative cooling degree days over the life of the contract. More generally, we can represent the payoffs of the weather puts and calls as:

$$Payoff\ Call : p(\$/DD) \times Max\left(0, X_{t|T} - K\right)$$
$$Payoff\ Put : p(\$/DD) \times Max\left(0, K - X_{t|T}\right)$$

where $p(\$/DD)$ is the per degree day payoff, $X_{t|T}$ is the underlying (CDD or HDD), and K is the strike (denominated in terms of the associated underlying measure).

An investor who is long (has purchased) a call option will receive the payoff if the recorded HDD or CDD for the season are greater than the Strike K. An investor who is long the put will receive the payoff if the HDD or CDD for the season are lower than the strike.

Call and Put Options with a Maximum Payoff (CAP)

In order to avoid excessive payouts on these contracts due to extreme weather, the options often come with a cap or maximum payoff.

$$Payoff\ Call : Min\left(p(\$/DD) \times Max\left\{0, X_{t|T} - K\right\}, h\right)$$
$$Payoff\ Put : Min\left(p(\$/DD) \times Max\left\{K - 0, X_{t|T}\right\}, h\right)$$

where h is the maximum payoff denominated in dollars.

$$Payoff\ Put : Min\left(p(\$/DD) \times Max\left\{K - 0, X_{t|T}\right\}, h\right)$$

Example of a Weather derivatives trader's pricing sheet

		Degree			Option	Bid	Offer	$DD	CAP
Location	WBAN	Days	Term	Strike	Type	($000)	($000)		$ Millions
Las Vegas	23,169	CDD	May-Oct	3210	Call	260	300	5,000	1
Philadelphia	13,739	CDD	Aug	370	Call	115	125	5,000	1

Weather Swaps

A swap is a combination of a call and put option with the same strike and on the same underlying location. Degree day swaps can provide revenue stability. The payoff is:

$$Min\left(p(\$/DD)\times Max\{0, X_{t|T} - K\}, h\right) - Min\left(p(\$/DD)\times Max\{0, K - X_{t|T}\}, h\right)$$

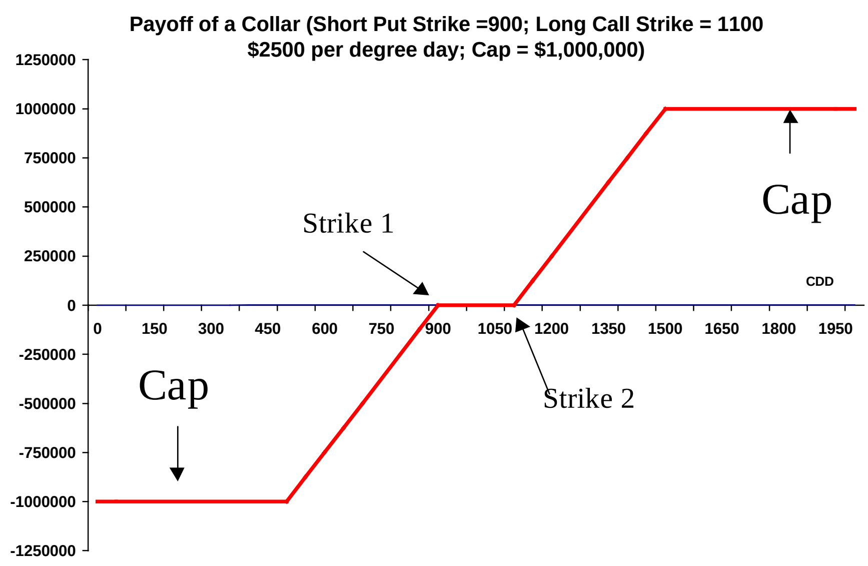
An investor who is long the swap will receive payments if the recorded HDD or CDD are greater than the strike, and will make payments if the recorded HDDs or CDDs are lower than the strike.

Collars or "fences"

Another spread position, a "collar," insulates the buyer from extreme movements in the underlying asset.

A collar typically consists of purchasing an OTM put (call) with a particular strike, and financing this with the sale of an OTM call (put) with a different strike. The general payoff is:

$$Min\left(p(\$/DD)\times Max\{0, X_{t|T} - K_1\}, h\right) - Min\left(p(\$/DD)\times Max\{0, K_2 - X_{t|T}\}, h\right)$$



Weather Derivatives Pricing Issues

RECENT MARKET DEVELOPMENTS

Weather derivatives markets have traditionally been characterized as having a small number of participants and large bid-ask spreads, but this is rapidly changing. During the last 18 months, the market has increased dramatically, and in the first semester of 1999 it is estimated that 800-1800 transactions have taken place in the United States, which represent a sharp increase from 100-150 transactions in 1997.

In the following table we can see the measuring stations and the ticker symbols of the futures contracts traded in the Chicago Mercantile Exchange.

{PRIVATE}City, State	Measuring Station (Airport)	Measuring Station (Symbol)	HDD Symbol	CDD Symbol
Atlanta, GA	Hartsfield Airport	ATL	H1	K1
Chicago, IL	O'Hare Airport	ORD	H2	K2
Cincinnati, OH	Covington, KY	CVG	H3	K3
New York, NY	La Guardia	LGA	H4	K4
Dallas, TX	Dallas-Fort Worth	DFW	H5	K5
Philadelphia, PA	Philadelphia International	PHL	H6	K6
Portland, OR	Portland, International	PDX	H7	K7
Tucson, AZ	Tucson Airport	TUS	H8	K8

Source: CME. http://www.cme.com/weather/symbols.html

PRICING MODELS FOR WEATHER DERIVATIVES

There are different ways to price weather derivatives. Before using any approach, it is important to the gain an intuitive understanding and make sure that the model is accurately capturing reality.

There are some pricing models that focus on the HDD or CDD directly, while others attempt to model temperature directly, and then extract the HDD or CDD for each temperature scenario. We think that modelling temperature directly is a substantially better approach. The problem with modelling HDD or CDD directly as a normal or lognormal process is that after we calculate the weather measures, a lot of information is lost (since, among other things, HDD and CDD are bound by zero).

In the following example, we can see a extreme example of what could happen if we model only degree days instead of temperature. Two cities with very different temperatures could have the same number of degree days.

Location A	1-Jan	2-Jan	3-Jan	Total HDD
1995	67	68	66	0
1996	65	55	65	10
1997	65	66	68	0
Location B	1-Jan	2-Jan	3-Jan	Total HDD
1995	85	83	81	0
1996	60	60	65	10
1997	79	81	80	0

Distribution of Weather Data; Trends and Seasonalities in Weather and choice of "Lookback Period".

Financial contracts derived from weather-specific measures, such as the expected future value of a local temperature, require the ability to predict regional weather conditions, months into the future. Thus, an effective model of the variations of a given weather-specific measure over the course of many months is essential for the accurate pricing of a weather derivative.

Just as financial traders rely on economic forecasts for trading strategies input, weather traders rely on meteorological forecasts for input on expected temperatures. Weather forecasting firms employ a variety of sophisticated models, involving many tens of parameters, to make both long and short range predictions about evolving weather conditions, both regionally and globally. However, regardless of the assumptions employed to model the behavior of weather-specific measures, one is confronted with inescapable truisms. Weather dynamics are governed by the laws of physics, from which yesterday's cold and damp overcast unfolds into today's warm, clear-blue sky - albeit with a measure of uncertainty. Uncertainty prevails when forecasting the weather, although short-term trends exist. In practice, this means that today's weather is more predictable than tomorrow's, and tomorrow's is more predictable than that for next week.

Understanding past weather patterns, including seasonal effects, is an important part of long-range weather forecasting. It is quite evident, for example, that many weather stations have experienced long-term warming, whether this arises from increasing urbanization, more local fossil fuel usage, or global warming. In the U.S. the National Weather Service (NWS) usually provides the data for such purposes.

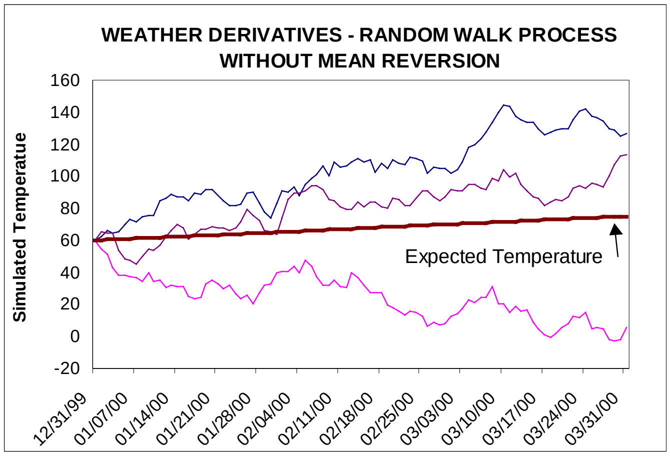
The most important decision to be made at the time of analyzing prior data used to price a weather derivative is the choice of the "lookback" period. This is the period of time in which to estimate average temperatures and volatilities. Common wisdom holds that 10-20 years of weather data may be required, and that accounting for trends and seasonalities is essentially *de rigor*.

Weather Derivatives Pricing Approaches

One of the main areas of controversy in the weather derivatives markets is the choice of the pricing methodology to use in order to obtain the "fair" value of the different contracts. Due to the lack of widely accepted weather derivatives pricing methodologies, counterparties do not always agree on the right price to trade.

a. Black-Scholes and Weather Derivatives

Fisher Black and Myron Scholes developed a model in 1973 to price put and call options that is still commonly used today. Unfortunately, the Black-Scholes model is based on certain assumptions that do not apply realistically to weather derivatives. One of the main assumptions behind the model is that the underlying of the contract (in our case HDD or CDD) follows a random walk without mean reversion. In other words, their model predicts that the variability of temperature increases with time, so temperature could wander off to any level whatsoever. In Figure 1. we can see different simulated daily temperature values for a three month period assuming that there is no mean reversion. The simulated temperatures differ substantially from expected temperatures, and we can see how the variability increases with time. We can see how this simulated temperatures are totally unrealistic, since towards the end of the simulation, we have temperatures as high as 140 and as low as 0 degrees for the same day of the year.

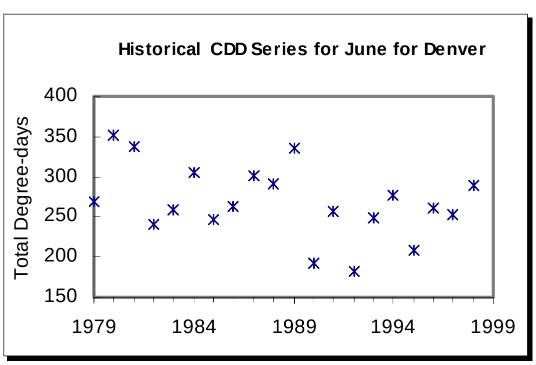


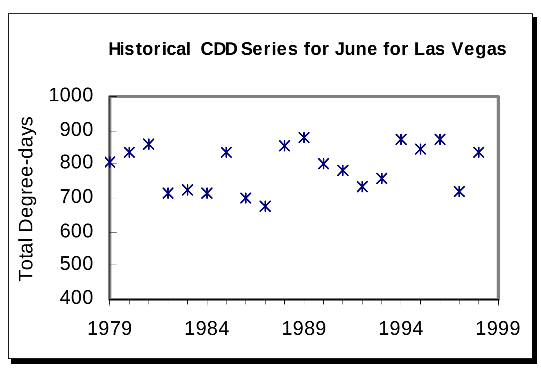
The Black-Scholes model is probably inadequate for weather derivatives for the following reasons:

- Weather does not "walk" quite like an asset price "random walk", which can in principle wander off to zero (think of degrees Kelvin) or infinity (hotter than the sun). Instead, variables such as temperature tend to remain within relatively narrow bands, probably because of a mean-reverting tendency, i.e. a tendency to come back to their historical levels.
- Weather is not "random" quite like an asset price random walk. Because of its inherent nature, weather is approximately predictable in the short run and approximately random around historical averages in the long run. This means that short-dated weather derivatives may behave fundamentally different than their long-dated counterparts.
- Black-Scholes option payoff is determined by the value of the underlying exactly at the maturity of the contract. Weather derivatives usually provide for *averaging* over a period of time, and are therefore are more akin to "Asian" or average price options, i.e. have a non-Black-Scholes payoffs.
- Many weather derivatives are also capped in payoff, unlike the standard Black-Scholes option.
- The underlying variables (e.g. temperature or precipitation) are not tradeable prices, and so pricing cannot be free of economy risk aversion factors, unlike the Black-Scholes model.

b. Simulations based on Historical Data or "Burn Analysis".

The "burn analysis" approach is very simple to implement and tries to answer the question: What would have been the average payoff of the option in the past X years? The main objection is that it does not incorporate temperature forecasts in its pricing.





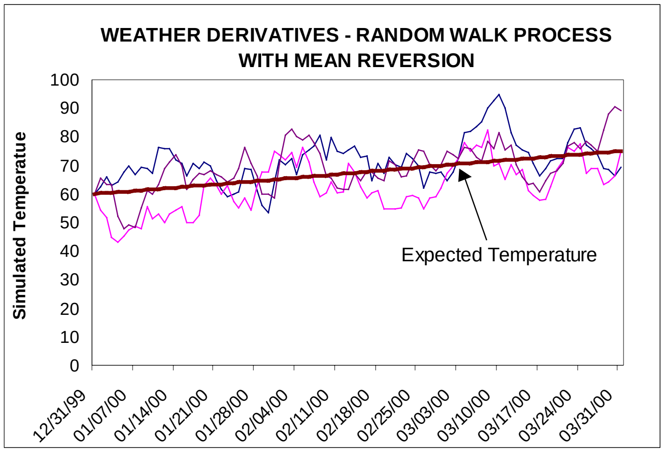
Using the yearly series of historically realized cumulative degree-days over the relevant instrument period we can determine the expected payoff for each year. The fair price of the option would be the average of those historical payoffs.

c. Monte Carlo Based Simulations

“Monte Carlo” is a computer-based method of generating random numbers which can be used to statistically construct weather scenarios. Such Monte Carlo simulations provide a flexible way to price different weather derivatives structures. Various types of averaging periods, such as those based on cumulating HDDs or CDDs, can be specified easily. Similarly, and as easily, a contractual cap placed on the price of the derivative can be taken into account.

Monte Carlo typically involves generating a large number of simulated scenarios of HDDs or CDDs to determine possible payoffs for the instrument. The fair price of the instrument is then the average of all simulated payoffs, appropriately discounted to account for the time value of money.

One can study a variety of stochastic processes of a given underlying weather-specific measure, say local temperature, whose parameters can be calibrated to the “lookback” period of available weather data.



For Monte Carlo based simulations, it is important to choose the right random process for temperature. It is reasonably clear that temperature is mean reverting, and therefore any models that only assume Black-Scholes style “random walk" behavior, will be inadequate to model temperature. Indeed, measurement of the reversion rate parameter in temperature data indicates that temperatures tend to revert to normal levels in 2 or 3 days.

SUMMARY AND CONCLUSION

The weather derivatives market needs a standard pricing model, so all participants can start communicating in a common language. At the moment, the major weather derivatives market makers have developed "black-box" models that they may not be willing to share with other participants. The large discrepancies between the different models used is preventing the market from developing at an even faster pace. Just as the Black-Scholes model for financial derivatives was one of the main driving factors of the option markets in the 1980s, the weather markets need a common denominator.

In our opinion, the "Burn Analysis" and mean-reverting Monte Carlo based simulation approaches offer maximum flexibility to price different instruments, and provide the necessary degree of accuracy and transparency to become a standard by which to price and trade these instruments.