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Weather derivative design in agriculture – a case study of barley in the Southern Moravia Region

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Abstract

The aim of this paper is to point out some problems of index estimation for the purposes of weather derivative valuation considering the particularities of agriculture. The assessment of the sensitivity of barley to weather over 40 years has been the basis for the design and valuation of weather derivative in the Czech Republic (The Southern Moravia Region). The analysis is based on regression modeling using temperature index and barley yield. The burn analysis based on parametric bootstrap is used as the method for the valuation of weather derivative contract. With the effective bootstrap tool, the burn analysis may easily be processed and the uncertainty about the pay-off, option price and statistics of probability distribution of revenues can be effectively determined. Nevertheless, the results of the analysis reveal a significant adverse impact of basis risk on the quality of agricultural weather derivative in the Czech growing conditions. The article outlines the scope for use of weather derivative as the reinsurance tool in regions with frequent occurrence of systematic weather risk.

Key words

Weather derivative valuation, agriculture, risk management, basis risk, burn analysis.

Anotace

Cílem příspěvku je poukázat na některé problémy spojené s odhadem indexu pro účely oceňování derivátů na počasí vzhledem ke specifikům zemědělství. Návrh derivátu na počasí v České republice (Jihomoravský kraj) je založen na analýze citlivosti výnosů ječmene na počasí v průběhu 40 let. Analýza je založena na metodě regrese analýzy s hektarovými výnosy ječmene jako závisle proměnnou a indexem teploty vzduchu jako vysvětlující proměnnou. Pro ocenění kontraktu je použita burn analýza založená na parametrickém bootstrapu. S efektivním nástrojem bootstrapu je možné snadno provést burn analýzu a určit nejistotu spojenou s výplatou a cenou opce a statistické charakteristiky rozdělení pravděpodobnosti tržeb. Výsledky nicméně odhalují výrazný nepříznivý vliv bazického rizika na kvalitu parametrických produktů v produkčních podmínkách ČR. Článek naznačuje prostor pro použití derivátů na počasí jako nástroje pro zajištění na úrovni regionů s četným výskytem systematických rizik počasí.

Klíčová slova

Oceňování derivátů na počasí, zemědělství, řízení rizik, bazické riziko, burn analýza.

Introduction

Weather hedging can be theoretically an appropriate risk management strategy for all companies whose earnings or cash flows are negatively affected by weather. A financial weather contract is a weather contingent contract whose pay-off will be determined by future weather events. The contract links payments to a weather index that is the collection of weather variables measured at a stated location during an explicit period (Dishel et al, 2002). Underlying "asset" of weather derivative are most often air temperature, rainfall, wind speed etc.

Financial weather contracts can be traded either in the form of weather derivative in the OTC (over-the-counter) markets and exchanges or through index insurance which is currently the most common way in agriculture. Trading in weather derivatives has been developing since the second half of the 90's of the 20th century. Dynamic growth in the number of traded contracts occurred after 2003, when the CME (Chicago Mercantile Exchange) offered clearing service center for weather derivatives. In the future, increasing interest in weather derivatives is expected, namely due to the development of energy production from renewable sources (solar power, wind, water), whose performance is dependent on weather.

Recently, weather derivatives have received considerable attention in the literature as potential risk management tools for agricultural production (Turvey, 2001; Martin, Barnett and Coble, 2001; Dishel et al, 2002; Vedenov and Barnet, 2004; Woodard and Garcia, 2008). All authors highlight both the benefits and problems of weather derivatives in comparison to conventional insurance products. Financial weather contracts that reduce transaction costs as pay-offs are based on an objectively measured index, so the farm-level loss adjustment is not needed. Weather derivatives and index insurance are free of moral hazard and adverse selection because market participants can not affect the index variable. Moreover, weather derivatives are suitable for transfer of systematic risk, because the higher spatial correlation of index variables determines the more liquid financial contract, which makes it easier to trade on the exchange market.

The major disadvantage of weather derivatives is basis risk. The basis risk refers to the potential discrepancy between actual loss and contract pay-off. Differences arising from the imperfect correlation between underlying weather variable and crop yield. The relatively larger the geographic area is, the higher basis risk can be observed. Nevertheless, weather derivatives are better to design for a relatively large area, because such contracts are easily marketable and more attractive to investors.

Weather derivatives are suitable for areas with most homogeneous production conditions, where farm income is significantly spatially correlated and spatial differences in the impact of weather on vegetation are low (Hess, 2007). The land relief affects the spatial distribution of precipitation and air temperature. The Czech Republic is characterized by heterogeneous production conditions. Relatively more homogeneous areas are the fertile lowlands of South Moravia, the Elbe valley and Haná. These areas are also most at risk of more frequent drought. On a global scale, there is greater homogeneity of the production conditions in the most intensively agricultural region of the U.S. Corn Belt than in the EU.

This paper aims to assess the effectiveness of agricultural weather derivative in the conditions of the Czech Republic. Since various combinations of weather variables, crops and weather stations create a huge number of potential weather derivatives, the scope of this paper enables only the weather derivative design and valuation of one crop in one region. The assessment of the sensitivity of barley to weather has been the basis for the design of weather derivatives in the South Moravia which represents a relatively homogeneous agricultural region. The weather derivative is designed for barley as one of the most significant crop planted in the Czech Republic.

Material and Methods

Temperature and precipitation are most important weather factors of yield variability. Weather data were obtained from the Czech Hydrometeorological Institute (CHMI). The analysis is based on daily / monthly average air temperatures and daily / monthly rainfall. The reference period is 40 years (1970-2009), which is sufficient time series to assess the dependence of yield on the weather. Monthly weather data are spatial averages of the data from meteorological stations in the Southern Moravia Region. Daily weather data were purchased from reference meteorological station Znojmo - Kuchařovice (334 meters above the sea level).

The series of barley yield in the South Moravian Region were obtained from the Czech Statistical Office. Since 2001 there has been a new delimitation of regional boundaries in the Czech Republic, so the average yield of barley prior to 2001 has to be adjusted to reflect the new regions. Adjustment of yield time series to the new territorial self-government structure is made using the data at the district level.

In order to account for temporal component, a simple detrending procedure is implemented by fitting the most suitable trend model (quadratic trend). We reveal the dependence between the barley yield and past weather using Pearson correlation coefficient. To avoid the possible omission of non-linear dependence between yield and weather variables, we also use Spearman rank correlation coefficient as an alternative indicator. Statistically significant correlation coefficients help to determine the critical month for yield formation of barley.

We adopt the following weather indices – air temperature (°C), rainfall (mm) and drought index[1] Si (combination of air temperature and rainfall). The underlying weather index with the highest correlation coefficient is the best index of weather derivative because it effectively reduces the basis risk.

In order to achieve the highest possible correlation between yield and weather variables, we set weights to the critical month of vegetation. The weights are optimized using the MS Excel Solver to find the highest value of correlation coefficient between yield and weather variable during the critical period of vegetation. So, the final index is a weighted average of the weather variables in the critical months of vegetation.

The weather derivative contract triggers (starts to pay) whenever the index gets bellow (rainfall) or above (temperature) a specified strike level. To clearly find the strike, we analyze the relationship between yield and index using simple linear regression. We set the strike as an expected post-harvest price (P) and regression coefficient (β). In order to choose multiple linear regression or polynomial regression, the strike cannot be clearly determined as it varies in different parts of the non-linear regression curve.

The regression function needs to be tested for autocorrelation (Durbin-Watson test at the significance level of 0.05, 40 observations, 2 predictors in the regression including a constant) and heteroskedasticity (parametric Goldfeld-Quandt test at the significance level of 0.05, Spearman rank correlation between independent variable and squared residuals).

In order to formally evaluate the efficiency of weather derivatives in reducing production risk, a particular contract layering and contract value must be set. Contract layering is based on the frequency and severity of risks which the farmer is not willing to accept and which he intends to share with other market participants. Firstly, we assume that farmer is willing to accept the decline in barley yield by 10% compared to the expected value (five-year average excluding the maximum and minimum).

In most cases, weather derivative pricing is based on actuarial method. Easy but effective actuarial method is burn analysis (or simply "burn"). Burn is based on the idea of evaluating how a contract would have performed in previous years (Jewson, Brix and Ziehmann, 2005). Burn analysis in this paper is enhanced by distribution fitting and Monte Carlo simulation.

The probability distribution of the independent variable (index) is estimated from the real data (1970 – 2009) using MLE method (Maximum Likelihood Estimation). As defined by Vose (2008), the maximum likelihood estimators of a distribution type are the values of its parameters that produce the maximum joint probability density for the observed dataset x. Consider a probability distribution type defined by a single parameter (α). The likelihood function L (α) that a set of n data points (x_i) could be generated from the distribution with probability density f (x).

$$L(X|\alpha) = \prod_i f(x_i,\alpha) \text{ ,i.e. } L(\alpha) = f(x_1,\alpha)\ f(x_2,\alpha)\ldots f(x_{n-1},\alpha)\ f(x_n,\alpha) \qquad (1)$$

The MLE is then the value of *α* that maximizes L (*α*). It is determined by taking the partial derivative of L (*α*) with respect to *α* and setting it zero:

$$\left.\frac{\partial L(\alpha)}{\partial \alpha}\right|_{\hat{\alpha}} = 0 \qquad (2)$$

Distribution fitting using MLE method is processed automatically[2] . The probability distribution is tested simultaneously with three goodness-of-fit tests at the significance level of 0.05 - Anderson-Darling test (A-D), Kolmogorov-Smirnov test (K-S) and χ^2 test.

It is very helpful to use the bootstrap tool (Efron, 1979) for improving burn analysis. Bootstrapping allows for easier estimation of uncertainty surrounding the estimate of mean and standard deviation of pay-off. We estimate the payoff uncertainty using the parametric bootstrap that requires the extra information about the probability distribution. The procedure of parametric bootstrap is as follows (Vose, 2008):

Collect the dataset of n samples (x_1, x_2,…, x_n).

Determine the parameter(s) of the distribution that best fit(s) the data from the known distribution family using maximum likelihood estimators (MLE).

Generate B bootstrap samples (x_1*, x_2*,…, x_n*) by randomly sampling from this fitted distribution.

For each bootstrap sample (x_1*, x_2*,…, x_n*), calculate the required statistic *θ*. The distribution

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[1] Since agricultural drought is a complex of many factors that cannot be included in one indicator, we use a drought index Si as an indicator of meteorological drought. The index S_i can be formulated as $S_i = \Delta_T/\sigma_T - \Delta_R/\sigma_R$. It presents a difference of monthly anomalies of temperature ($\Delta_T = t - tn$) and precipitation ($\Delta_R = r - rn$) to their standard deviations σ_T and σ_R (Potop, Türkott and Kožnarová, 2008).

[2] The probability distribution of risk factors is estimated using the software module BatchFit Oracle Crystal Ball 11.1.

of these B estimates of θ represents the bootstrap estimate of uncertainty about the true value of θ.

Contract pricing is based on an estimate of a "fair" price, i.e. price at which the expected profit for both contracting parties is zero. The contract price (in this case of an option) is the average expected contract pay-off. Nevertheless, the seller of the option would probably expect a reward for taking on the risk of having to pay out, and hence the premium would probably be slightly higher than the expected payoff by a risk loading. We set the risk loading as 20 % of the standard deviation of the payoff of the contract (Jewson, Brix and Ziehmann, 2005)

Efficiency of weather derivative to reduce risk is quantified by comparing the distribution of revenues from barley sales including hedging and without hedging. If the farmer does not buy a weather derivative contract, he would realize the revenues $R_{0.}$

$$R_0 = \frac{\int Q_T(I_T)P}{(1+r_f)^n} \tag{3}$$

Q_T denotes barley yield (t/ha) being a function of stochastic variable I_T. P is expected postharvest crop price (CZK/t). Since the expected pay-off ($Q_T \cdot$ P) is related to the beginning of the contract period (usually 1 year), it should be discounted by using risk free rate rf (e. g. 1-year PRIBOR rate at 30th June 2010 was 1.76 %).

If the farmer buys a weather derivative contract per 1 ha of crop, he has to pay the premium to the seller (F_0). On the other hand, farmer may collect a pay-off from the contract (F_T) if a weather variable exceeds the strike (Weber et al, 2008). The payment is a function of underlying weather index I_T.

$$R_1 = R_0 + \frac{\int F_T(I_T)}{(1+r_f)^n} - F_0 \tag{4}$$

The effectiveness of hedging is assessed by comparing the coefficient of variation of revenues with and without using derivatives. Calculation is performed by using Monte Carlo simulation method with 10 000 iterations at the significance level of 0.05. The degree of basis risk is quantified by comparing simulation without standard error (without basis risk) and including standard error in regression estimate (including basis risk).

Results and Discussion

Table 1 presents the results of correlation analysis between barley yield and weather. The table lists the most significant correlation coefficients, including the test of statistical significance. As might be expected, a statistically significant moderate relationship had occurred between the yield of barley and air temperature in April, May, June (and July). Precipitations are local, so the risk of lack or, conversely, excessive rainfall has a systematic character. In addition to the sensitivity of barley due to the lack of precipitation in spring, inverse relationship is shown between yield and rainfall during the pre-sowing soil preparation. The correlation between barley yield and precipitation at the regional level is rather weak.

Region/station	Temperature (°C)	Precipitation (mm)	Drought index Si
South Moravia	-0.64 (6, p < 0.0001)	0.36 (4-6, p = 0.0218)	-0.60 (4-6, p < 0.0001)
	-0.64 (5-6, p < 0.0001)	0.33 (4-5, p = 0.0387)	-0.56 (5-6, p = 0.0002)
	-0.63 (4-6, p < 0.0001)	-0.32 (3, p = 0.0439)	-0.49 (4-5, p = 0.0012)
	-0.55 (4-7, p = 0.0002)		-0.47 (6, p = 0.0020)
	-0.54 (5-7, p = 0.0003)		-0.47 (5, p = 0.0021)
Station Znojmo-Kuchařovice	-0.60 (6, p < 0.0001)	X	-0.61 (4-6, p < 0.0001)
	-0.59 (5-6, p < 0.0001)		-0.57 (5-6, p = 0.0001)
	-0.58 (4-6, p < 0.0001)		-0.53 (6, p = 0.0005)
	-0.51 (4-7, p = 0.0008)		-0.48 (4-7, p = 0.0015)
	-0.50 (5-7, p = 0.0010)		-0.47 (4-5, p = 0.0021)

Notes: The data in front of round brackets are correlation coefficients. The figures in brackets denote critical months for yield formation. and p-values test the two-tailed statistical significance of the correlation coefficient. The term „X“ indicates no statistically significant correlation (Pearson. Spearman) at significance level 0.05. We put a maximum of 5 most statistically significant correlation coefficients.
Source: Author.

Table 1: The most significant correlation coefficients between barley yield per hectare and the average characteristics of weather in the Southern Moravia Region (1970 – 2009).

Due to the systematic effect of air temperature and drought on barley yield at the regional level, the following weather indexes were put to the regression analysis:

- weighted average air temperature from May to June (T 2)
- weighted average air temperature from April to June (T 3)
- weighted drought index Si from May to June (Si 3)
- weighted drought index Si from April to June (Si 3)

Table 2 summarizes the results of testing the effect of various weather indices on barley yield. The results of correlation analysis indicate that the most appropriate index (i.e. index with minimum basis risk and highest correlation) for the weather derivative in the Southern Region is weighted average temperature from April to June. The largest weight (65.7%) is assigned to the average air temperature in June, the smallest weight to the month of May (14.9%). Dependence is statistically significant both at the 0.05 and 0.01 significance levels.

Example	T 2	T 3	S_i 2	S_i 3
Month (weights)	5 (0.264)	4 (0.194)	5 (0.500)	4 (0.271)
	6 (0.736)	5 (0.149)	6 (0.500)	5 (0.307)
		6 (0.657)		6 (0.422)
Pearson r	-0.666	-0.688	-0.592	-0.645
	(p < 0.0001)	(p < 0.0001)	(p < 0.0001)	(p < 0.0001)
R2	0.443	0.473	0.350	0.416
	(p < 0.0001)	(p < 0.0001)	(p < 0.0001)	(p < 0.0001)

Source: Author.

Table 2: Relationship between the barley yield and weather indices in the South Moravia.

Region/station	Linear fit	R^2	Adjusted R^2	D-W test	p-value
South Moravia	y = -0.3623x + 9.5613	0.473	0.460	1.840	< 0.0001
Station Znojmo- -Kuchařovice	y = -0.3052x + 8.7431	0.405	0.390	1.840	< 0.0001

Source: Author.

Table 3: Results of the regression analysis for barley.

The relationship between barley yield and selected index is expressed by the regression functions in table 3.

Linear trend explains fluctuations in barley yield in the critical months of the year of around 47%. Choosing non-linear trend does not dramatically improve the quality of fit (e. g. 4-order polynomial trend has the R^2 of only 0,483). Neither Spearman rank correlation nor Goldfeld-Quandt test revealed the existence of heteroscedasticity.

According to Anderson-Darling goodness-of-fit test, residuals come from the normal distribution[3]. Standard error is 0.442. This information is used to quantify the effectiveness of contract involving basis risk.

Three goodness-of-fit tests of weather index (A-D, K-S, χ^2) indicate that the selected weather index comes from the logistic distribution with mean 15.02 and scale 0.62. P-value of Anderson-Darling test (0.776) is satisfactory.

Considering the above mentioned regression equation for the contract to barley, the expected yield of barley 4.1 t/ha can be achieved when the weighted average air temperature in April-June exceeds 15.07°C. We also suppose that farm is willing to accept the decline in barley yield by 10% compared to the expected value. The critical value of yield is then 3.7 t/ha which can be reached at the critical temperature of 16.18°C. The probability of exceeding this critical temperature (strike) is approximately 14%. So, this weather derivative will cover high-risk low-probability systematic event of high air temperatures.

Option price is set by burn analysis using parametric bootstrap. The average pay-off ranges from 109 to 117 CZK per contract (the mean is 113 CZK) with a probability of 95%. The standard deviation of

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[3] Anderson-Darling test = 0.15, p-value = 0.957.

the pay-off ranges between 359 and 383 CZK per contract (the mean is 371 CZK) with a probability of 95%. The price of option contract is thus possible to set of CZK 113 + 20% (risk loading) of 371 CZK, i. e. ca 190 CZK.

Based on the results of correlation and regression analysis and following the selection and testing of an appropriate index, it is possible to determine the structure of the contract. Table 4 contains the specification of weather derivative for barley in South Moravia. Table 5 presents statistics of the probability distribution of barley revenues.

	Specification
Contract type	Call option
Contract size	1 ha of barley
Index	Weighted average air temperature (°C)
Location/station	South Moravia/average of stations (CHMI)
Accumulation period (Weights)	April (0.194). May (0.149). June (0.657)
Strike	16.18°C
Fixed price	3 700 CZK per tonne of barley
Tick	1 341 CZK per 1°C above strike
Contract period	1 year (July 1st 2010 – June 30th 2011)
Premium	190 CZK per contract incl. risk loading

Source: Author.

Table 4: Structure for specific-event contract (barley. South Moravia) – call option. long without capping.

	Without basis risk		Including basis risk	
	Without hedging	Hedging	Without hedging	Hedging
Trials	10 000	10 000	10 000	10 000
Mean	14 946	14 876	15 006	14 932
Median	14 958	14 768	15 007	14 866
Standard Deviation	1 478	1 269	2 181	2 046
Skewness	0.0540	0.8545	0.0087	0.1921
Kurtosis	4.25	4.17	3.18	3.12
Coeff. of Variability	*0.0989*	*0.0900*	*0.1453*	*0.1370*
Minimum	7 361	13 259	6 858	7 948
Mean Std. Error	15	13	22	20

Source: Author.

Table 5: Statistics of the probability distribution of revenues (barley. CZK per 1 contract).

In case of hedging, the effectiveness of weather derivative contract is relatively low - farmers could reduce the variability of revenues only by 5.7 % if we take the basis risk into account. The analysis revealed a very high basis risk, which may result in both excessive and poor pay-off. If we consider no basis risk, the contract could help reduce the variability of revenues by 13.8 %. However, the basis risk really exists.

These results confirm the findings by Vedenov and Barnett (2004), Weber et al (2008), Manfredo and Richards (2009) emphasizing in particular the disadvantages of weather derivatives as primary crop insurance instruments. Nevertheless, the aggregation effect suggests that the potential for weather derivatives in agriculture may be greater than previously thought, particularly for aggregators of risk, such as reinsurers (Woodard and Garcia, 2008).

Conclusion

The results revealed a significant adverse impact of the basis risk on the quality of parametric products. The effectiveness of weather derivatives as the risk management instruments could be higher in areas with more homogeneous production conditions (than in the Czech Republic) and more light sandy soils, where rainfall directly determines the flow of water to plant roots and water gets quickly into the lower soil layers being out of reach for plant roots.

The main limitation on the use of weather derivatives in the Czech Republic are heterogeneous production conditions that reduce the correlation between rainfall and crop yields at regional level. Unavailability of data at the district level makes impossible to make in-depth analysis of the smaller territorial units. Conversely, the main opportunity for use of weather derivatives in the Czech Republic is a dense, high-quality network of meteorological stations with long-term data availability, which creates an appropriate basis for further research of other crops and regions.

The use of weather derivatives should be of interest mainly to the regional agricultural organizations and associations through which they can manage the systemic risks of weather. If we assume the potential of weather derivatives as the reinsurance instrument, it is important to clarify the legal and institutional aspect of the income risk management in agriculture using weather derivatives, especially regulation and possible areas of cooperation between the public and private sector.

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