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THE INFLUENCE OF METEOROLOGICAL CONDITIONS ON DAIRY PRODUCTION

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Abstract

Relatively little attention has been paid in the economics literature to the effects of meteorological conditions on milk production. Meteorological variables can be expected to affect milk production through their impact on the productivity of cows and foodstuff production. Rather than including meteorological variables as inputs in the milk production process, we propose a production function where temperature and humidity directly affect the productivity of cows and where a series of meteorological variables can affect the productivity of expenditure on foodstuff, thereby indirectly affecting milk production. Using production and meteorological data from the Spanish region of Asturias corresponding to 382 dairy farms observed during a 6-year period from 2006 to 2011, the results from our estimated production function show the important impact of meteorology on dairy production. On average, we find a difference of 10% in variable profits due to operating under favourable or unfavourable weather conditions.

Keywords: weather conditions, dairy farms, production function, panel data.

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1. Introduction

Agriculture is perhaps the economic activity most dependent on meteorological conditions and the climatic change that the planet has been undergoing in recent years (IPCC, 2013) has led to a growing interest among researchers in the evaluation of the impact of meteorological conditions on agriculture. The economic evaluation of the influence of climatic conditions has been analysed from various perspectives. Some studies have evaluated the influence of meteorological conditions on land value (Mendelsohn *et al.*, 1994; Schlenker *et al.,* 2006) and agricultural profits (Deschênes and Greenstone, 2007). Regarding the effects on productivity, Demir and Mahmud (2002) and Barrios *et al.* (2008) have studied the impact of meteorological variables on agricultural productivity from an aggregate perspective. Several other studies have considered the impact of meteorology on farms' productivity for specific crops. For example, Sherlund *et al.,* (2002) and Tanaka *et al.,* (2011) evaluate the impact of meteorology on rice production; Isik and Devadoss (2006) analyse its effect on the production of wheat, barley, potato and sugar; and Chen *et al.,* (2013) estimate the influence of meteorology on grain productivity.

However, whereas considerable effort has been devoted to the analysis of the effect of meteorology on dairy farming by animal scientists (St. Pierre *et al*., 2003; Bohmanova *et al*., 2007; Mader *et al*., 2010), few economic studies so far have analysed its effect on milk production. Kompas and Che (2006) use a dummy variable to control for a drought period and Moreira *et al*. (2006) also use dummy variables to control for differences in climatic conditions in different geographical zones. To the best of our knowledge, only one published study (Mukherjee *et al.,* 2013) specifically takes into account the impact of meteorological variables on dairy farm productivity.

Mukherjee *et al.* (2013) analyse the productivity of dairy farms in Florida and Georgia, which are some of the warmest states in the United States. It is considered that cows can suffer from so-called *heat stress*, which can negatively affect their productivity. In this study, we follow Topp and Doyle (1996) in considering that meteorology can affect both cows' thermal comfort and foodstuff production on the farm. As these effects of meteorology can be of the opposite sign (for example, an increase in temperature may reduce cows' productivity due to heat stress while simultaneously improving forage production) they can cancel each other out and make them difficult to identify. To resolve this identification issue, we propose a model in which meteorological variables influences cows' productivity and foodstuff production in a separable way.

The rest of the paper is organized as follows. Section 2 briefly defines the concept of the thermal comfort index developed by animal scientists and describes the Temperature and Humidity Index which is the index used in this paper. Section 3 develops the model for the analysis. Section 4 describes the data used in the empirical analysis, which proceeds from two different sources: yearly farm data proceeding from nine Dairy Farmer Management Associations located in the region of Asturias (Spain) and daily meteorological data provided by the Spanish State Meteorological Agency, AEMET (*Agencia Estatal de Meteorología*), which are provided from 10 automated meteorological stations spread across the territory of the region. The results of the empirical analysis are presented in Section 5, and Section 6 presents the main conclusions.

2. Thermal comfort indexes

Animal scientists have closely studied the effects of weather conditions on animal performance. In particular, it has been well demonstrated that dairy cow performance is heavily affected by heat stress, and several variables have been used to evaluate this influence. Some studies (Barash *et al.,* 2001; Andre *et al.,* 2011) use temperature to evaluate the incidence of heat stress on dairy cows. However, the animals' thermal comfort is also influenced by other variables apart from temperature such as relative humidity, wind speed and solar radiation. Consequently, most studies use some thermal comfort index which encompasses several meteorological variables to obtain an apparent (or "feel like") temperature. Several thermal comfort indexes have been developed by animal scientists and there is an ongoing effort to develop more accurate indexes (Mader *et al.*, 2010).[1]

The most commonly used thermal comfort index in dairy studies is the so-called Temperature and Humidity Index (hereafter, THI) constructed with data on temperature and relative humidity. This index has been used to evaluate the impact of cows'

[1] Paim *et al.* (2012) considers the relative performance of 8 different classes of thermal comfort indexes in approaching the thermal comfort of lambs.

thermal comfort in several studies using data from different countries with very different climatic conditions. Among these, Ageeb and Hayes (2000) analyses the case of Sudan, Broucek *et al.* (2007) use data from Slovakia, Bryant *et al.* (2007) consider the case of New Zealand, Solymosi *et al.* (2010) analyse the case of Hungary and St. Pierre *et al.* (2003) use data from the US. We consider the THI an appropriate thermal comfort index for our study as survey results from 2007 have shown that only a small minority (15%) of farmers in our sample let cows graze, and the cows were always returned to the stable at the end of the day. Thus, most cows in our sample are not exposed to wind, rainfall and sun.

It is worth noting that THI should be understood as a family of indexes and several alternative formulae can be used for its calculation. Dikmen and Hansen (2009) compare the relative performance of 8 different formulae for the calculation of the THI. In this paper we use the formula proposed by Yousef (1985) for THI calculation, which has been used by Ageeb and Hayes (2000) and Mukherjee *et al.* (2013), among others. According to this, the THI is calculated on a daily basis using the formula:

$$THI = 41.2 + T_a + 0.36T_{dp} \tag{1}$$

where T_a is the average daily temperature and T_{dp} is the dew point temperature.[2] The dew point temperature was not provided by AEMET (State Meteorological Agency). However, the air temperature, the relative humidity and the dew point temperature are related in a non-linear way that can be approximated using the formula:

$$T_{dp} = \frac{243.5 \times \gamma}{17.67 - \gamma} \tag{2}$$

where γ is defined as:

$$\gamma = \ln\left(Hu + \frac{17.65 \times T_a}{243.5 + T_a}\right) \tag{3}$$

with *Hu* being the average daily relative humidity.

In our empirical model we will include the THI as a variable conditioning the productivity of cows. However, the fact that cows in our sample are generally not exposed to wind,

[2] The dew point is the temperature at which the water vapour content in the atmosphere starts to condense into liquid water; that is, is the temperature that generates 100% relative humidity with the current water vapour content in the atmosphere.

rainfall and sun does not mean that these factors are irrelevant to milk production. In particular, both the quantity of forage obtained as well as its nutritional quality depend on weather conditions. This is especially true of rainfall, temperature and the amount of sunlight, and the effects of these factors on feed production will also be taken into account in our empirical model.[3]

3. Model Specification

We consider that milk production (y) is carried out using cows (x_1), expenditures on feed production inside the farm (x_2), labour (x_3), concentrates (x_4), forage purchases (x_5) and animal expenses (x_6). The State Meteorological Agency (AEMET) provides daily data on a series of weather variables including temperature (MV_1), humidity (MV_2), rainfall (MV_3), wind (MV_4) and sun exposure (MV_5). We incorporate the weather variables into our analysis by assuming that they are not direct inputs in milk production but instead that these variables can influence the productivity of some of the production factors used by farmers. In particular, we consider that cows' productivity is affected by temperature (MV_1) and humidity (MV_2), and we therefore include the THI defined above as a determinant of that productivity. On the other hand, we consider that the whole set of meteorological variables can influence the production of feed inside the farm. Hence, we define the production function:

$$y = F(f_1(x_1, THI), f_2(x_2, MV_1, \dots, MV_5), x_3, \dots, x_6) \tag{4}$$

where $F(\cdot)$ is the production function that characterizes the technology and $f_1(\cdot)$ and $f_2(\cdot)$ are the functions that captures the influence of meteorological variables on the productivity of cows and expenditures on feed production inside the farm respectively. Therefore, this model assumes that meteorological variables do not have any *direct* impact on milk production but that this impact comes through its influence on the productivity of cows and the expenses on foodstuff production. Additionally, in accordance with the expected influence of meteorology the model assumes that $f_1(\cdot)$ and $f_2(\cdot)$ are separable from the remaining inputs aside from cows and foodstuff, implying that meteorological variables do not have a *direct* effect on the productivity of

3 See, for example, the following Penn State Cooperative Extension website devoted to forage quality: http://www.forages.psu.edu/topics/forage_qa/index.html. See also the US EPA website for information on the effects of climate change on feed and livestock: http://www.epa.gov/climatechange/impacts-adaptation/agriculture.html.

these inputs. As cows are generally inside the cowshed, the model captures the idea that only temperature and humidity (*THI*) directly affect cows' productivity whereas the complete set of weather variables is allowed to affect feed production. It should be highlighted that the *indirect* effects of weather variables on other inputs productivities will be allowed in the model through second-order effects: thus, the productivity of, say, concentrates will depend on the values of $f_1(\cdot)$ and $f_2(\cdot)$, which in turn depend on weather conditions.

To specify the functions $f_1(\cdot)$ and $f_2(\cdot)$ we take into account the fact that farm data are provided on a yearly basis while meteorological data are provided on a daily basis. As the influence of weather variables on agricultural production is related not only to average meteorological values but also to their variability throughout the year, we aggregate the weather variables as follows. First, each year is split into two periods: the cold period which includes January, February, March, October, November and December, and the warm period that comprises the central part of the year from April to September. For each period we consider two characteristics of the distribution of the meteorological variables, namely their average and a measure of the variability of weather conditions within the period (the standard deviation of each variable). Hence, the function $f_1(\cdot)$ is defined as follows:

$$f_1(\ln x_1, THI) = \ln x_1 + \sum_{p=1}^{2} \gamma_p THI_{AVG_p} + \sum_{p=1}^{2} \delta_p THI_{V_p} \tag{5}$$

where subscripts *AVG* and *V* stand for the average and variability of daily THI during the period. Subscript *p* refers to the cold (*p* = 1) and warm (*p* = 2) periods within the year.

In a similar way the function $f_2(\cdot)$ is defined as follows:

$$f_2(\ln x_2, MV_w) = \ln x_2 + \sum_{w=1}^{5}\sum_{p=1}^{2} \delta_{wp} MV_{AVG_{wp}} + \sum_{w=1}^{5}\sum_{p=1}^{2} \delta_{wp} MV_{V_{wp}} \tag{6}$$

where the subscript *w* (*w* = 1,…,5) stands for the five different meteorological variables provided by AEMET. For each weather variable we also consider two periods within the year and we include its average and its standard deviation as a dispersion measure.

We assume that the function $F(\cdot)$ takes a translog functional form. To take into account possible technological differences due to geographical characteristics we include the dummy variable *Interior* which is equal to 1 for farms located in an interior (inland) county and equal to zero for farms located in coastal counties. We also included a set of year dummy variables in order to capture differences in productivity due to technical progress and other variables generating differences in productivity along the years. We thus specify a translog production function where the functions $f_1(\cdot)$ and $f_2(\cdot)$ are included as arguments substituting cows (x_1) and expenditures on foodstuff production (x_2):

$$\ln y = TL(f_1(\ln x_1, THI), f_2(\ln x_2, MV_1, \dots, MV_5), \ln x_3, \ln x_4, \ln x_5, \ln x_6,) + \beta_I Int + \sum_{t=2007}^{2011} \beta_t D_t + e \quad (7)$$

where $TL(\cdot)$ denotes the translog functional form and D_t is a vector of time dummy variables. Therefore, the impact of weather conditions on milk production is captured through its direct effect on the productivities of cows and expenditure on foodstuff production. However, as the translog is a flexible functional form, the indirect effects of weather on other input productivities and output elasticities are also captured in the model through the second-order terms.

4. Data

4.1. Economic data

The empirical application is carried out using data from dairy farms located in the region of Asturias in northwest Spain. Asturias is one of main milk-producing regions in Spain, and milk production accounted for 52% of total agricultural production in the region in 2011.

The data used in the empirical analysis consists of an unbalanced panel of 1,325 observations corresponding to 382 dairy farms observed during a 6-year period from 2006 to 2011. Those farms were enrolled in a voluntary record-keeping program conducted by the regional government. This program collects information about nine

Dairy Farmer Management Associations located in Asturias. These associations are funded by the regional government and their main objective is to provide management advice to its affiliated farmers. To collect the data necessary for the managerial advisory service, each farm is visited on a monthly basis by a technician. The monthly information is then combined with annual inventories to prepare an annual report on each farm.

The dependent variable in the model is the *production of milk* (y) and is measured in litres. As mentioned above, six inputs are considered: *cows* (x_1), defined as the number of adult cows in the herd;[4] *foodstuff production expenditure* (x_2), defined as the costs of seeds, fertilizer, fuel, land, other raw materials and machinery hire and amortization;[5] *labour* (x_3), which includes family labour and hired labour and which is measured using Social Security expenses; *concentrate feeds* (x_4) is the amount of concentrates used by the farm measured in kilograms; *forage purchases* (x_5), defined as expenditure on the acquisition of forage; and *animal expenses* (x_6), which includes expenditure on veterinary services, milking, electricity, water and the amortization of buildings and technical installations. All the above monetary variables are expressed in 2011 euro. Table 1 shows the descriptive statistics of output and inputs.

Table 1: Output and input statistics

	Mean	**Std. Dev.**	**Minimum**	**Maximum**
Milk	390173	281297	22685	2672774
Cows	49	29	6	249
Foodstuff production expenditure	23350	19656	850	161627
Labour	4959	2623	221	20838
Concentrate feed	184969	142911	11855	1220100
Forage purchases	8813	12574	10	176843
Animal expenses	17193	13558	563	129699
Interior	0.478	0.500	0	1

Differences among farms are quite large as the standard deviation of milk production is 72% of the mean production. The average farm size in the sample is larger than the average Spanish farm (31 cows in 2010; Eurostat, 2014) but quite similar to the average farm size in some of the main milk producing countries in Europe such as France or Germany (46 cows; Eurostat, 2014).

[4] All the farms in the sample use Holstein-Frisian cows.

[5] Ray-grass, corn and natural and cultivated pastures are the main forage crops in Asturias.

4.2. Meteorological data

The data on meteorological variables are provided by AEMET. The data come from 10 meteorological stations spread across Asturias, which has an area of 10,604 km², and includes daily values of temperature (maximum, minimum and average) measured in degrees Celsius, relative humidity (maximum, minimum and average) measured as the actual vapour content in the atmosphere as a percentage of the maximum vapour content, rainfall measured in litres per square metre, maximum wind speed measured in kilometres per hour, and hours of sun exposure. Data on average daily values of temperature and humidity are calculated as the arithmetic mean of maximum and minimum daily values.

The daily data are grouped in two periods. The cold period comprises January, February, March, October, November and December while the warm period comprises the central part of the year from April to September. Each farm is assigned the weather information corresponding to its nearest meteorological station following two criteria. First, farms and meteorological stations are classified into two groups: coastal and interior. This is a relevant classification because in Asturias the mountains are near to the coast and the meteorology can be quite different among relatively nearby areas depending on whether there are mountains between a given area and the coast. Thus, each farm is assigned to the closest meteorological station within its group: coastal farms are assigned to their closest coastal meteorological station and interior farms are assigned to their closest interior meteorological station. Second, each farm and year is assigned the data corresponding to the mean and variability (standard deviation) of daily meteorological variables in each one of the two periods within the year. Tables 2 and 3 show descriptive statistics of the mean and standard deviation of the meteorological variables assigned to the farms in the sample.[6]

[6] These statistics were calculated taking the farms, not the meteorological stations, as the basis. That is, once the meteorological data from the closest interior or coastal station are assigned to each farm we calculate the mean and standard deviations of the meteorological variables for each six-month period using the daily observations of all the farms assigned to a particular station.

Table 2: Mean values of weather variables

	Cold period				Warm period			
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	**54.74**	**1.37**	**51.67**	**58.03**	**62.64**	**0.82**	**60.59**	**64.44**
Temp. max.	**14.75**	**0.85**	**12.58**	**16.16**	**20.88**	**1.26**	**17.53**	**23.75**
Temp. min.	**6.95**	**1.33**	**4.45**	**9.60**	**12.69**	**0.97**	**11.11**	**15.58**
Hum. max.	**93.89**	**2.76**	**85.34**	**98.07**	**94.83**	**2.38**	**87.96**	**99.09**
Hum. min.	**60.67**	**2.46**	**53.39**	**65.45**	**62.37**	**4.82**	**53.95**	**74.46**
Rainfall	**3.39**	**0.83**	**1.58**	**5.72**	**1.91**	**0.60**	**0.82**	**3.09**
Wind	**33.19**	**10.23**	**11.16**	**54.62**	**28.26**	**6.60**	**9.36**	**41.77**
Sun	**3.85**	**0.54**	**2.76**	**4.78**	**5.59**	**0.46**	**4.82**	**6.50**

Table 3: Standard deviations of weather variables

	Cold period				Warm period			
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	4.93	0.77	3.54	6.28	4.41	0.64	3.10	5.69
Temp. max.	4.36	0.79	2.65	5.76	3.92	0.78	2.49	5.64
Temp. min.	3.83	0.51	2.63	4.82	3.30	0.45	2.27	4.17
Hum. max.	6.29	1.24	3.88	8.82	3.80	1.07	1.46	6.41
Hum. min.	13.73	1.46	11.09	17.24	12.51	1.25	9.52	14.42
Rainfall	6.93	1.75	4.19	12.48	5.35	1.99	2.46	11.66
Wind	18.85	7.35	4.72	33.26	11.27	4.69	2.95	19.42
Sun	3.22	0.18	2.87	3.53	4.17	0.18	3.81	4.43

Tables 2 and 3 show that climate conditions are rather temperate in Asturias. Temperatures are not very different between the cold and the warm periods. Humidity is always high as it is a coastal region and the differences in humidity between the cold and warm periods are small. Rainfall and wind are relatively high and there are moderate differences between the cold and warm periods, especially for rainfall. Finally, sun exposure is not too high and is moderately higher in the warm period, as would be expected given the relatively small differences in the durations of day and night along the year which correspond to the latitude of the region of Asturias (43º N). Comparing the values corresponding to maximum and minimum temperatures, it seems that in the cold period the minimum temperatures are more disperse than the maximum temperatures, whereas in the warm period the opposite occurs. Hence, in the empirical application we use the minimum temperature for the cold period and the maximum temperature for the warm one. The opposite occurs with relative humidity and therefore maximum humidity is used in characterizing the cold period while minimum humidity is used for the warm period.

5. Results and discussion

For comparative purposes, we first estimate the translog production function for milk ignoring the meteorological variables. The parameter estimates are shown in Table 4. The logarithms of the inputs were transformed by subtracting their sample mean, so that the first-order coefficients of the inputs can be interpreted as the output elasticities for a representative farm characterized by an input endowment equal to the sample geometric mean.

Table 4: Production function parameters without including climatic variables

Parameter	Estimate	t-statistic	Parameter	Estimate	t-statistic
Constant	12.702***	1061.04	**ln $x_2 \times$ ln x_6**	-0.014	-0.56
ln x_1	0.448***	23.28	**(ln x_3)^2**	0.030	1.32
ln x_2	0.100***	11.18	**ln $x_3 \times$ ln x_4**	-0.051*	-1.71
ln x_3	0.050***	5.47	**ln $x_3 \times$ ln x_5**	-0.009	-1.24
ln x_4	0.330***	25.46	**ln $x_3 \times$ ln x_6**	-0.066***	-2.59
ln x_5	0.027***	6.78	**(ln x_4)^2**	-0.191***	-4.52
ln x_6	0.113***	9.54	**ln $x_4 \times$ ln x_5**	-0.023**	-2.30
(ln x_1)^2	-0.073	-0.75	**ln $x_4 \times$ ln x_6**	0.023	0.62
ln $x_1 \times$ ln x_2	0.003	0.06	**(ln x_5)^2**	0.008**	2.44
ln $x_1 \times$ ln x_3	0.151***	3.44	**ln $x_5 \times$ ln x_6**	-0.013	-1.37
ln $x_1 \times$ ln x_4	0.084	1.47	**(ln x_6)^2**	0.000	0.01
ln $x_1 \times$ ln x_5	0.037**	2.40	**Interior**	-0.021***	-2.63
ln $x_1 \times$ ln x_6	0.056	1.05	**D_{2007}**	-0.008	-0.58
(ln x_2)^2	0.056**	2.02	**D_{2008}**	-0.047***	-3.56
ln $x_2 \times$ ln x_3	0.016	0.86	**D_{2009}**	-0.055***	-4.02
ln $x_2 \times$ ln x_4	-0.046*	-1.75	**D_{2010}**	-0.053***	-3.89
ln $x_2 \times$ ln x_5	-0.004	-0.54	**D_{2011}**	-0.043***	-3.21
R^2	0.962				

*** 1% level of significance; ** 5% level of significance; * 10% level of significance

As we would hope, all first-order coefficients (output elasticities) are positive and significant. The output elasticity of the cows is the largest, as has been found in other studies. This elasticity is slightly lower than the ones found by Lawson *et al.* (2004), Moreira and Bravo-Ureta (2010) or Mukherjee *et al.* (2013). The labour elasticity is positive and significant and in the range found by Lawson *et al.* (2004) and Mukherjee et al (2013), while other studies have found a non-significant elasticity (Ahmad and

Bravo-Ureta, 1995; Cuesta, 2000). The scale elasticity (1.069) shows slightly increasing returns to scale and on the basis of a Wald test is statistically larger than 1 at any usual level of significance. This is in the range found by del Corral *et al.* (2011). The dummy variable *Interior* is negative and significant, indicating that coastal farms are more productive than the interior ones. It is worth noting that the time dummy variables are all negative and significant except for the one corresponding to 2007, showing that productivity significantly decreased over the sample period. In light of the genetic progress observed in Asturias since the beginning of the century (Roibas and Alvarez, 2010; Roibas and Alvarez, 2012), this fall in productivity may be considered surprising.

Table 5: Production function parameters including climatic variables

Parameter	Estimate	t-statistic	Parameter	Estimate	t-statistic
Constant	12.683***	378.94	$f_2(\cdot) \times \ln x_6$	-0.035**	-2.02
$f_1(\cdot)$	0.451***	23.77	$(\ln x_3)^2$	0.044*	1.94
$f_2(\cdot)$	0.086***	9.82	$\ln x_3 \times \ln x_4$	-0.054*	-1.86
$\ln x_3$	0.050***	5.45	$\ln x_3 \times \ln x_5$	-0.010	-1.32
$\ln x_4$	0.337***	25.86	$\ln x_3 \times \ln x_6$	-0.052**	-2.08
$\ln x_5$	0.029***	7.17	$(\ln x_4)^2$	-0.198***	-4.64
$\ln x_6$	0.112***	9.35	$\ln x_4 \times \ln x_5$	-0.019*	-1.88
$(f_1(\cdot))^2$	-0.009	-0.12	$\ln x_4 \times \ln x_6$	0.032	0.87
$f_1(\cdot) \times f_2(\cdot)$	-0.010	-0.36	$(\ln x_5)^2$	0.010***	3.04
$f_1(\cdot) \times \ln x_3$	0.168***	4.43	$\ln x_5 \times \ln x_6$	-0.013	-1.44
$f_1(\cdot) \times \ln x_4$	0.036	0.68	$(\ln x_6)^2$	0.015	0.43
$f_1(\cdot) \times \ln x_5$	0.037***	2.81	**Interior**	-0.041**	-2.41
$f_1(\cdot) \times \ln x_6$	0.050	1.04	D_{2007}	-0.007	-0.14
$(f_2(\cdot))^2$	0.053***	3.48	D_{2008}	-0.016	-0.31
$f_2(\cdot) \times \ln x_3$	-0.002	-0.17	D_{2009}	-0.033	-0.88
$f_2(\cdot) \times \ln x_4$	-0.008	-0.43	D_{2010}	-0.015	-0.36
$f_2(\cdot) \times \ln x_5$	-0.007	-1.47	D_{2011}	-0.034	-0.84
R^2	0.964				

We now turn to the estimates of the production function with the meteorological variables included. This production function, equation (7) was estimated by non-linear least squares. The logarithm of the inputs were transformed, as before, by subtracting their sample mean and same transformation was applied to the meteorological variables. Consequently, the first-order parameters can be interpreted as output elasticities for a representative farm characterized by an input endowment equal to the sample geometric mean and which produces under the weather conditions corresponding to the sample average value of the meteorological variables. In particular, the first-order parameters corresponding to $f_1(\cdot)$ and $f_2(\cdot)$ can be interpreted as the elasticities of cows and foodstuff production expenses *under average meteorological conditions*. Table 5 shows the parameter estimates when meteorological variables are included in the model.[7]

As can be seen by comparing Tables 4 and 5, the estimates with and without meteorological variables are quite similar, especially when focusing on the first-order parameters. In particular, the estimated coefficients on $f_1(\cdot)$ and $f_2(\cdot)$, which represent the elasticities of cows and foodstuff production under sample-average weather conditions, are very similar to the corresponding coefficients when weather is not taken into account. Even the scale elasticity is quite similar in both estimations, taking a value of 1.066 when meteorological variables are included (also statistically larger than 1 at any usual level of significance according to the Wald test).

This is not to say, however, that weather variables do not matter. The most important difference between the estimates with and without the meteorological variables concerns the dummy variables capturing time and location effects. When the meteorological variables are included, none of the time dummy variables is significant, whereas all except one were highly significant in the previous estimation. Therefore, it seems that differences in productivity along the sample period can be explained by differences in meteorological conditions over the period. Another important difference relates to the variable distinguishing coastal from interior farms. The dummy variable *Int* is negative and significant, as it was when the meteorological variables were excluded, but the estimated value of the parameter when meteorological variables are included is almost double the value it takes when these variables are not included (-0.041 vs -0.021). Hence, differences in productivity according to geographical location may be underestimated if meteorological conditions are not taken into account.

We now turn to the effects of individual weather variables on the productivity of cows and foodstuff. Table 6 shows the estimates of the coefficients of the weather variables which enter the functions $f_1(\cdot)$ and $f_2(\cdot)$.

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[7] The estimates of the parameters included in $f_1(\cdot)$ and $f_2(\cdot)$ are shown in Table 6.

Table 6: Meteorological parameters

Average of weather variables					
Cold period			**Warm period**		
Parameter	**Estimate**	**t-statistic**	**Parameter**	**Estimate**	**t-statistic**
Effect on cow productivity			***Effect on cow productivity***		
THI	0.028	1.32	**THI**	-0.054**	-2.26
Effect on foodstuff productivity			***Effect on foodstuff productivity***		
Temperature	-0.094	-0.45	**Temperature**	0.423*	1.89
Humidity	0.123*	1.92	**Humidity**	0.059	1.37
Rainfall	-0.537	-1.32	**Rainfall**	-0.124	-0.31
Wind	-0.117***	-2.63	**Wind**	0.085**	2.15
Sun	-2.519***	-3.43	**Sun**	0.098	0.17
Variability of weather variables					
Cold period			**Warm period**		
Parameter	**Estimate**	**t-statistic**	**Parameter**	**Estimate**	**t-statistic**
Effect on cow productivity			***Effect on cow productivity***		
THI	0.101**	2.12	**THI**	-0.075	-1.34
Effect on foodstuff productivity			***Effect on foodstuff productivity***		
Temperature	-0.833*	-1.74	**Temperature**	0.163	0.40
Humidity	0.256**	2.17	**Humidity**	0.024	0.15
Rainfall	0.166	0.98	**Rainfall**	-0.244**	-2.30
Wind	0.094**	2.10	**Wind**	-0.133**	-2.55
Sun	3.807**	2.52	**Sun**	-0.331	-0.35

From Table 6 it is clear that meteorology affects the productivity of cows and foodstuff production, and thereby milk production, as 13 of the 24 estimated parameters are significant. Looking at the effect of weather conditions on cow productivity, it seems that cows suffer from heat stress in the warm period as the coefficient interacting with the average THI in that period is significantly negative. This is not a surprising result since heat stress was found to be significant in the Netherlands (Andre *et al.*, 2011) where the climatic conditions are similar though somewhat colder than those in Asturias. It is interesting to note that the variability of THI significantly increases cows' productivity in the cold period, which suggests that cows are more comfortable with some variability in weather conditions during the cold period.

Turning to the effect of weather variables on foodstuff production we find that high temperatures favour feed production during the warm period, which may be expected. It is also observed that greater variability of temperatures during the cold period has a negative effect on foodstuff production. As the minimum daily average temperatures are above 0ºC for each month in each meteorological station, greater variability of minimum temperatures inevitably implies freezing days, which diminishes forage production.[8]

The average and variability of relative humidity only have a positive effect on forage production during the cold period, when high relative humidity favours foodstuff production as might be expected *a priori*.[9]

Only one parameter related with rainfall is significant. This may be due to the fact that rainfall is rather stable in Asturias and neither drought episodes nor unusually large rainfalls were found in the sample period. The significant coefficient is that on rainfall variability in the warm period, and its negative value shows that rainfall concentration in a few days can harm foodstuff production. It is worth noting that from the 10th to the 16th of June, 2010, rainfall accumulation caused serious floods in valley zones in Asturias.

The four parameters on the wind variables are significant and show opposing influences in the cold and the warm periods. In the cold period, high average wind speed diminishes foodstuff productivity, whereas it increases foodstuff productivity in the warm period. Therefore, it seems that in the warm period the wind collaborates in forage pollination. However, in the cold season the average wind speed is higher than in the warm period and is found to diminish foodstuff productivity. We also find that stability in the wind speed during the warm period improves foodstuff productivity, whereas the opposite happens in the cold period.

Sun exposure was found not to be significant in the warm period, which could be due to the relative stability of sun exposure over the warm period in the different years and locations. However, both the average and variability of sun exposure are significant in the cold period. The effect of average sun exposure is negative, which may be due to the fact that during the cold season sunny days are associated with large differences between maximum and minimum temperatures. However, the variability of sun exposure is found to have a positive effect and the concentration of sun exposure in a few days is therefore found to have a positive effect on foodstuff production.

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[8] Minimum daily average temperatures are positive each month in each meteorological station, so the observation of freezing days necessarily implies some variability of minimum temperatures around their average values.

[9] It can be observed from the daily data that the variability of relative humidity is larger when the minimum temperature is positive than when it is negative. In light of this, the positive effect of the variability of relative humidity can be related to the scarcity of freezing days.

It is worth highlighting the importance of allowing for potentially different effects of weather variables on cow productivity and foodstuff production. This is especially relevant in the case of temperature, where we find that high temperatures have two counteracting effects on milk production. Our results show that high temperatures generate heat stress in cows and thereby decrease their productivity, which in turn reduces milk production. However, high temperatures have a positive effect on foodstuff production. Therefore, if the model does not allow for potentially different effects of temperature on the productivity of cows and foodstuff production, the effect of heat stress could be underestimated due to the compensatory effect of temperatures on forage production.

In an attempt to quantify the effects of the meteorological variables on farm performance, we exploit the estimated production function parameters by simulating some weather scenarios and calculating their impact on production and profits.

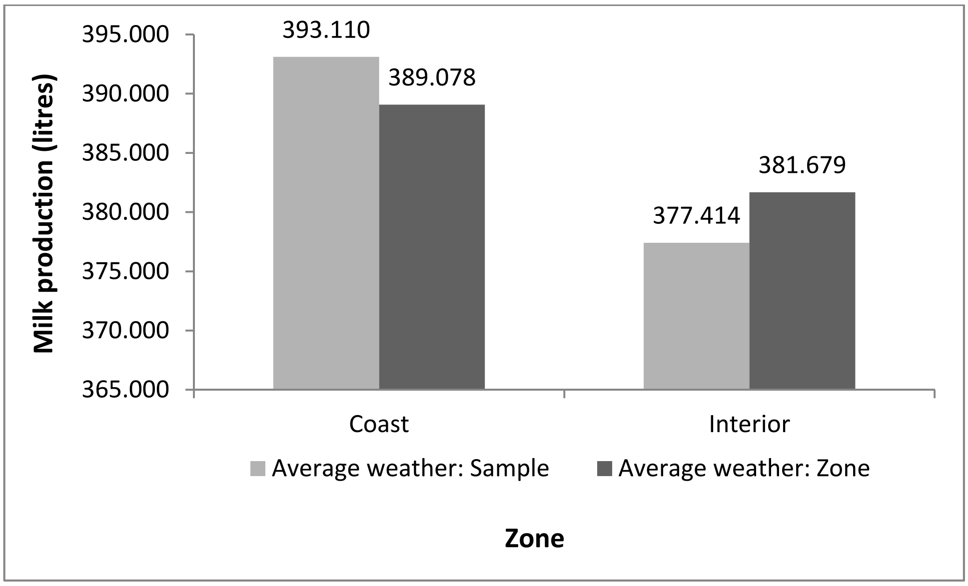

Figure 1. Milk production for farms in coastal and interior zones: expected production for average weather in sample vs. average weather in zone.

We make the distinction between farms located in coastal and interior zones of the region. As an initial simulation exercise, we compare the expected production of farms in coastal and interior zones under average weather conditions for the sample as a whole with their expected production under average weather conditions in each zone.

As can be seen in Figure 1, under the average weather conditions for the sample as a whole, expected production levels for the representative farms in the coastal and interior regions are 393,110 and 377,414 litres, underlying the fact that coastal farms have structural advantages over interior farms, the latter having, in general, more hilly terrain. If these representative farms operated under the average weather conditions of their respective areas, the gap between them narrows: the expected production of the representative coastal farm would fall to 389,078 litres while that of the representative interior farm would rise 381,679 litres. Thus, while coastal farms have structural advantages, weather conditions tend to mitigate these differences.

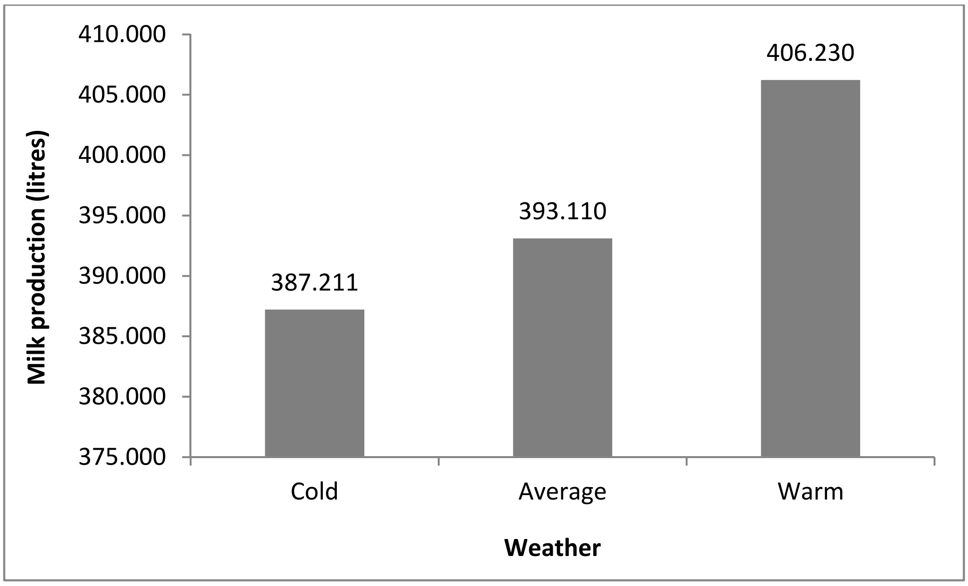

Figure 2. Milk production for farms in coastal zone according to type of weather

As a further illustration of the effect of weather on production, Figure 2 compares predicted (i.e., expected) milk production for the representative farm in coastal areas[10] under cold, average and warm conditions. The first step in this analysis is to assign values to the meteorological variables corresponding to "warm" and "cold" years. To identify values corresponding to a warm year, we calculate the (arithmetic) mean of all the meteorological variables for observations where the maximum temperature is higher than the average maximum temperature in the sample period. This is done separately for the cold period of the year and the warm period. The values corresponding to a cold year are calculated in a similar way, i.e., we calculate the mean

[10] Given that the difference between coastal and interior farms is reflected in the *Interior* dummy variable, it makes no difference which type of farm we choose. We choose coastal farms because they are more productive.

of the meteorological variables for observations where the maximum temperature is below the sample average of the maximum temperatures, carrying out these calculations separately for the cold and warm periods. The warm and cold periods are then combined to construct cold and warm years.[11]

As can be seen, the differences are quite substantial. Compared to an expected production of 393,110 litres for this representative farm under average weather conditions in the sample, in a typical cold year the farm's output would fall to 387,211 (a drop of 1.5%) while in a warm year it would rise to 406,230 (an increase of 3.3%). To see how this translates into revenues, the price of a litre of milk in the final year of the sample, 2011, was 0.339€. Hence, expected revenues for the representative farm in cold, average and warm weather are 131,125€, 133,122€ and 137,565€ respectively. The change in operating conditions from warm to cold weather therefore leads to a reduction of 6,500€ in revenue. Given that the average value of the expenditure on forage production, concentrate feed, forage purchases and animal expenses is approximately 80,000€, this translates into a reduction in variable profits of approximately 10%.

Finally, comparing the production predicted by the model under actual weather conditions for each individual observation with its predicted production if weather conditions corresponded to those of the sample mean, we find that the standard deviation of production was 16,584 litres. This represents 6.1% of average production predicted by the model under actual weather conditions, highlighting the significant swings in production that can be caused by weather.

6. Summary and conclusions

The process of climatic change that the planet is undergoing has increased the interest of economic studies evaluating the effect of meteorological conditions on agriculture. However, despite the attention devoted by animal scientists to the effect of weather on dairy production, only one recent economic study (Mukherjee *et al.*, 2013) has analysed the effect of meteorology on milk production. Our analysis extends the results

[11] The values of the variables corresponding to the different meteorological scenarios are included in Appendix 1.

found by Mukherjee *et al.* (2013) in two different respects. First, the empirical analysis is carried out with data from a geographical zone with a temperate climate, whereas Mukherjee et al (2013) analyse the effect of meteorology with data from Florida and Georgia, which are among the warmest states in US. Second, our analysis extends the model applied in Mukherjee et al (2013) by considering the effect of meteorology not only on cows' thermal comfort but also on foodstuff production inside the farm. To accomplish this objective we construct a production model in which the meteorological variables are included in a separable way in the production function in order to assess the expected impact on cows' productivity, on the one hand, and the influence on foodstuff production on the other.

Our results show the important impact of meteorology on dairy production. When the meteorological variables are not included in the analysis, our estimation found that farm productivity was roughly 5% lower in the years 2008-2011 than it was in the years 2006 and 2007, which may be considered surprising given the genetic improvement in cows observed in Asturias since the turn of the century. However, when the effect of weather is considered, no statistically significant differences in productivity are observed during the sample period. Therefore, it seems that meteorology is responsible for important differences in productivity in dairy farming. Additionally, our model shows some counteracting effects of meteorology on milk production. High temperatures in the warm season improve foodstuff production, on the one hand, while causing cows to suffer from some heat stress on the other. Thus, if farms use a large proportion of self-produced foodstuff and the effect of meteorology on forage production is not considered, the results obtained may underestimate the effect of cows heat stress on milk production. In turn, these negative effects of meteorological conditions on milk production through heat stress imply that measures to improve the acclimatization of parlours may be justified.

A simulation analysis allows us to quantify the effects of weather conditions on milk production and, by extension, revenues. For the representative coastal farm, milk production when operating under warm weather conditions is 5% higher than when operating under cold conditions. This translates into a difference in profits of approximately 10%. We further find that coastal farms have a structural advantage over farms in the interior when it comes to milk production but that this difference is mitigated by weather conditions. Finally, we compare predicted milk production for individual producers under their actual weather conditions with their predicted production if their weather conditions had been those at the sample mean. The standard deviation amounted to over 6% of mean production, underlining the influence of water conditions on production performance.

For a more complete assessment the impact of weather conditions on milk production, more research is needed in several directions. Milk production is carried out in several geographic zones around the world and the effect of weather will depend on the climatic conditions in each zone, which will condition both the thermal comfort of cows and also the use of different forage crops that will be affected by meteorology in a different way to those harvested in Asturias. Different milking cow breeds could also be affected by meteorology in different ways and the data in this study correspond uniquely to Holstein-Frisian cows. Also, alternative management practices (grazing, mobile milking parlours, etc.) could lead to different production technologies that may not be affected in the same way by meteorology.

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APPENDIX 1: Weather variable values used in simulations

Values of weather variables for warm year

Table A1: Mean values for warm year

	Cold period				Warm period			
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	55.51	0.86	53.32	58.03	63.09	0.71	61.88	64.44
T. max.	15.32	0.39	14.78	16.16	22.17	0.88	20.91	23.75
T. min.	7.65	1.08	4.75	9.60	12.23	0.84	11.22	15.58
H. max.	93.01	2.86	85.34	98.07	95.57	1.52	90.26	98.90
H. min.	60.30	2.35	53.39	64.87	58.16	4.41	53.95	67.50
Rainfall	3.07	0.77	1.58	4.78	1.91	0.61	1.05	3.09
Wind	35.38	12.26	11.16	54.62	28.24	3.72	9.36	35.11
Sun	3.88	0.51	3.23	4.78	5.75	0.29	5.17	6.11

Table A2: Standard deviations for warm year

	Cold period				Warm period			
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	4.58	0.68	3.71	6.02	4.88	0.54	3.80	5.69
T. max.	4.05	0.76	3.04	5.59	4.70	0.57	3.45	5.64
T. min.	3.68	0.49	2.96	4.59	3.59	0.42	2.65	4.17
H. max.	6.07	1.14	3.88	8.77	3.62	0.53	1.70	5.27
H. min.	13.63	1.32	11.46	16.93	12.83	1.13	10.37	14.42
Rainfall	6.40	1.64	4.19	9.83	5.36	2.06	2.46	9.64
Wind	20.76	8.74	4.72	33.26	8.12	2.13	3.31	14.02
Sun	3.25	0.16	3.03	3.53	4.30	0.11	4.16	4.43

Values of weather variables for cold year

Table A3: Mean values for cold year

	Cold period				Warm period			
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	53.70	1.22	51.67	56.12	62.33	0.75	60.59	64.13
T. max.	13.98	0.67	12.58	14.73	20.01	0.51	17.53	20.88
T. min.	6.01	1.02	4.45	9.42	13.00	0.94	11.11	15.07
H. max.	95.08	2.10	88.59	97.63	94.33	2.71	87.96	99.09
H. min.	61.16	2.51	53.80	65.45	65.23	2.38	61.09	74.46
Rainfall	3.83	0.71	2.00	5.72	1.91	0.59	0.82	2.97
Wind	30.23	5.32	12.65	50.38	28.28	7.99	9.46	41.77
Sun	3.81	0.59	2.76	4.44	5.48	0.52	4.82	6.50

Table A4: Standard deviations for cold year

	Cold period				Warm period			
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	5.40	0.61	3.54	6.28	4.08	0.47	3.10	4.95
T. max.	4.78	0.62	2.65	5.76	3.39	0.35	2.49	4.43
T. min.	4.04	0.47	2.63	4.82	3.11	0.35	2.27	3.90
H. max.	6.58	1.32	4.25	8.82	3.93	1.30	1.46	6.41
H. min.	13.87	1.63	11.09	17.24	12.30	1.28	9.52	14.38
Rainfall	7.64	1.64	4.44	12.48	5.35	1.94	2.73	11.66
Wind	16.28	3.52	5.55	26.97	13.39	4.75	2.95	19.42
Sun	3.18	0.19	2.87	3.53	4.08	0.16	3.81	4.32

<u>Mean values of weather variables for coastal farms</u>

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Table A5: Mean values for coastal farms

	Cold period				Warm period			
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	55.56	0.78	53.72	58.03	62.51	0.86	60.59	64.44
T. max.	15.08	0.61	12.95	16.07	20.03	0.60	17.53	21.47
T. min.	7.96	0.69	6.76	9.60	13.28	0.90	12.05	15.58
H. max.	92.31	2.56	85.34	96.46	93.83	2.67	87.96	98.14
H. min.	59.71	2.58	53.39	64.87	65.39	2.55	61.09	74.46
Rainfall	3.21	0.82	1.58	4.73	1.81	0.61	0.82	2.97
Wind	36.44	12.53	11.16	54.62	28.17	8.96	9.36	41.77
Sun	3.57	0.45	2.76	4.46	5.41	0.50	4.82	6.50

Table A6: Standard deviations for coastal farms

	Cold period				Warm period			
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	4.58	0.67	3.54	5.60	4.08	0.49	3.10	4.73
T. max.	3.84	0.50	2.65	4.51	3.33	0.28	2.49	3.74
T. min.	3.69	0.48	2.63	4.46	3.14	0.38	2.27	3.62
H. max.	6.65	0.99	4.88	8.82	4.13	1.28	1.93	6.41
H. min.	13.09	0.80	11.46	15.92	12.46	1.32	9.52	14.42
Rainfall	6.46	1.64	4.19	9.83	5.26	2.13	2.46	11.66
Wind	21.39	8.64	4.72	33.26	13.84	4.89	2.95	19.42
Sun	3.18	0.20	2.87	3.53	4.09	0.16	3.81	4.32

Mean values of weather variables for interior farms

Table A7: Mean values for interior farms

	Cold period				Warm period			
Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	53.84	1.30	51.67	56.19	62.77	0.76	61.31	64.20
T. max.	14.38	0.92	12.58	16.16	21.81	1.13	19.36	23.75
T. min.	5.85	0.92	4.45	8.86	12.04	0.55	11.11	14.89
H. max.	95.61	1.75	88.19	98.07	95.93	1.35	87.96	99.09
H. min.	61.72	1.81	56.73	65.45	59.08	4.56	53.95	67.78
Rainfall	3.59	0.80	2.19	5.72	2.02	0.56	1.05	3.09
Wind	29.65	4.89	22.79	45.24	28.36	1.94	17.09	35.11
Sun	4.16	0.47	3.23	4.78	5.78	0.32	4.82	6.50

Table A8: Standard deviations for interior farms

	Cold period				Warm period			
	Mean	**Std. Dev.**	**Min.**	**Max.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
THI	5.31	0.67	3.72	6.28	4.76	0.59	3.44	5.69
T. max.	4.93	0.65	3.10	5.76	4.56	0.63	2.91	5.64
T. min.	3.99	0.51	3.02	4.82	3.49	0.45	2.62	4.17
H. max.	5.89	1.37	3.88	8.07	3.45	0.60	1.46	5.75
H. min.	14.43	1.69	11.09	17.24	12.57	1.17	9.52	14.42
Rainfall	7.44	1.73	4.95	12.48	5.46	1.82	2.46	9.64
Wind	16.08	4.11	10.86	28.40	8.46	2.18	5.20	17.31
Sun	3.26	0.14	3.03	3.53	4.25	0.15	3.81	4.43