SFB 649 Discussion Paper 2011-077

Increasing Weather Risk: Fact or Fiction?

Weining Wang*
Ihtiyor Bobojonov*
Wolfgang Karl Härdle*
Martin Odening*

* Humboldt-Universität zu Berlin, Germany

This research was supported by the Deutsche Forschungsgemeinschaft through the SFB 649 "Economic Risk".

http://sfb649.wiwi.hu-berlin.de
ISSN 1860-5664

SFB 649, Humboldt-Universität zu Berlin
Spandauer Straße 1, D-10178 Berlin

SFB 649 ECONOMIC RISK BERLIN

Increasing Weather Risk: Fact or Fiction? *

Weining Wang[1], Ihtiyor Bobojonov[2], Wolfgang Karl Härdle[3], Martin Odening[4]

Abstract

It is an undisputed fact that weather risk increases over time due to climate change. However, qualification of this statement with regard to the type of weather risk and geographical location is needed. We investigate the application of novel statistical tools for assessing changes in weather risk over time. We apply local *t*-test, change point tests and Mann-Kendall test as well as quantile regression to weather risk indicators that are relevant from the viewpoint of agricultural production. Our results show that weather risk follows different pattern depending on the type of risk and the location.

Keywords: weather extremes, agricultural risk, change point test, quantile regressions

JEL classification: C00, C14, J01, J31

1 Introduction

A wide range of scientific studies provides empirical evidence for increasing weather risk (e.g. Tebaldi et al., 2006, Vasiliades et al., 2009). Nevertheless, we believe that the statistical measurement of weather risk and weather extremes deserves further attention. The main message of this paper is that the "increasing-weather-risk" hypothesis needs to be qualified in several directions. First, there is no single clear definition of weather risk and meaning of weather risk is often not obvious. This is not surprising, since different sectors in an economy

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* The financial support from the Deutsche Forschungsgemeinschaft via CRC 649 "Economic Risk", Humboldt-Universität zu Berlin is gratefully acknowledged.

[1] Research associate at the Institute for Statistics and Econometrics of Humboldt-Universität zu Berlin, Germany

[2] Research associate at the Department of Agricultural Economics, Humboldt-Universität zu Berlin, Germany

[3] Professor at Humboldt-Universität zu Berlin and Director of C.A.S.E. - Center for Applied Statistics and Economics, Berlin, Germany

[4] Professor at the Department of Agricultural Economics, Humboldt-Universität zu Berlin, Germany

Correspondence to: M. Odening (m.odening@agrar.hu-berlin.de)

are affected in a very specific, complex and often nonlinear manner by weather events. Second, the finding of the studies demonstrating increased risk over time may be valid only for the locations, where weather data have been recorded. It is not trivial to draw conclusions about the change of weather risk in other locations (Vasiliades et al., 2009). Third, the time dimension of increasing weather risk needs further investigation. An important aspect for predicting future risk exposures is to know if weather risk increases steadily over time or increase is characterized by jumps and discontinuities. Finally, improving the methodology of assessing weather risk trends is considered as one of the important topics in the field of risk and uncertainty assessment (Hegerl et al., 2007; Tebaldi et al., 2006).

In this paper a battery of statistical test procedures is utilized, among them a local *t*-test, the change point test and the commonly used Mann-Kendall test. Moreover, upper and lower quantiles and their confidence bands are estimated using quantile regression. These techniques are applied to four weather indices, two of them are temperature based (Growing Degree Days (GDD), Frost Days Index (FDI)) and two are rainfall based (Cumulative Rainfall Index (CRI) and Potential Flood Index (PFI)). These indicators have been used in earlier studies on weather risk exposure in agriculture (e.g. World Bank, 2005). The objective of this paper is to describe the historical pattern of the weather risk indicators and to test for significant changes over time. Our results are illustrative and not comprehensive due to the limited number of weather indices and locations we analyse here. However, the suggested procedures can be easily applied to other weather events and locations. Our contribution to the existing literature is twofold. First, we apply local tests instead of global tests. Estimation is done nonparametrically allowing for a flexible estimation of the trends, both in means and in quantiles. Second, we apply alternative tests for trend detection.

2 Methodology

2.1 Local tests for the trend in weather variables

There are numerous approaches available for assessing the existence of trend in time series data. The *t*-test and the Mann-Kendall test are among the most commonly used methods to examine if the value of the time series data increases or decreases over time. The change point test is another important statistical method widely used to analyse the time series data for sudden jumps. Global tests, however, which consider a fixed, predetermined observation period, may not be able to indicate when a change of weather risk occurred. Andriyashin et al.

(2006) introduce a localized version of a *t*-test, a change point test and a Mann-Kendall test, where the whole observation period is divided into smaller sub periods. In this study we apply localized versions of all three tests mentioned above. An advantage of local tests is the possibility of examining when exactly changes happen. Such tests can also better detect a local behavior in the data and check if there are upward and downward trends in the observation period.

As an example, we demonstrate the localization of the *t*-test. The Mann-Kendall test and the change point test can be localized in a similar fashion. The main idea of the *t*-test is to identify if the slope of the linear model is significantly different from zero. The linear model has the form:

$$m(j) = \alpha + \beta j \quad j = 1,...,n, \qquad (1)$$

where *n* is the number of observations, $m(j)$ denotes the mean function $E(Y_j)$. Y_j is the temperature or rainfall index, and α and β are the intercept and slope parameters. These parameters are estimated by minimizing the sum of squares:

$$(\hat{\alpha}, \hat{\beta}) = argmin_{\alpha,\beta} \sum_j \{Y_j - \alpha - \beta j\}^2 \qquad (2)$$

The statistical significance of the slope parameter β, i.e. the trend, is tested by the null hypothesis $\beta = 0$, and $\beta \neq 0$ otherwise. Test statistics (t^*) are defined as:

$$t^* = \frac{\hat{\beta} - 0}{\tilde{\sigma}}, \qquad (3)$$

where $\tilde{\sigma}$ is from the residuals of the linear model in Eq. (2), and t^* asymptotically converges to a *t* distribution with n-2 degree of freedom. Instead of assuming linearity of $m(j)$ in Eq. (1) for the whole sample period one can divide the data set into small subintervals (windows) *L* and estimate the parameters α_L, β_L for each window *L*. Under this condition, parameters α and β may also change with respect to subintervals (windows). The sequence of test results is interpreted by P-values, i.e. the probability of test statistic to fall in the rejection region of the null hypothesis. We identify change points only if a sufficient number of consecutive significant signals in the P-values sequence occur. How consecutive they should be is basically controlled by aggregation parameters τ and κ.

τ indicates the minimum number of subsequent P-values eligible to create a summation measure and κ is the maximum number of insignificant P-values to drop the summation to zero. To decide when exactly a change is considered to be significant a threshold value η for the cumulative P-values needs to be specified. There is no common agreement on how to select the aggregation parameters τ and κ and the threshold value η although these are very important hyper parameters that affect the outcome of the tests. Following Andriyashin et al. (2006) we set the value of τ equal to 4 and κ equal to 2. The threshold value η is set to the half of the maximum accumulated P-value.

We apply the same idea of localization to the change point test and the Mann-Kendall test. In what follows we briefly review these two tests in a global setting.

The (global) change point test divides the data into two sub intervals and tests whether there is a significant difference between the means in two sub intervals, which are denoted as L_1 and L_2 with n_1 and n_2 number of observations each respectively. We calculate the sample mean for both of the intervals as follows:

$$\mu_i = \frac{1}{n_i}\sum_{j}^{n_i} Y_j \quad i = 1,2 \qquad (4)$$

The null hypothesis assumes equal means $\mu_1 = \mu_2$ and the alternative is $\mu_1 \neq \mu_2$. The test statistics V can be estimated as:

$$V = \frac{n_1 n_2}{n_1 + n_2} \frac{(\hat{\mu}_1 - \hat{\mu}_2)^2}{\tilde{\sigma}^2}, \qquad (5)$$

where V asymptotically converges to a $\chi^2(1)$ distribution and $\tilde{\sigma}$ is the unknown standard error estimated from residuals. Residuals are estimated using the whole sample with $n = n_1 + n_2$ observations:

$$\tilde{r}_j = Y_j - \hat{m}_h(j) \quad j = 1,\ldots,n \qquad (6)$$

Herein $\hat{m}_h(j)$ denotes the local constant nonparametric estimator (cf. Härdle, 1990).

The Mann-Kendall test (global) is a nonparametric test widely used in studies related to climate change and weather extremes (e.g. Wang and Swail, 2001; Adamowski et al., 2003). This test compares the value of each point with the subsequent data values. The standardized test statistics is:

$$S^* = \frac{\sum_{i=2}^{n}\sum_{j=1}^{i-1} sign(y_i - y_j)}{\sqrt{n(n-1)(2n+5)/18}}, \qquad (7)$$

where S^* has an asymptotic standard normal distribution. A significant positive value of S indicates an increasing trend whereas a negative value indicates a decreasing trend.

2.2 Quantile Regression and Bands

Quantile regression is one of the widely used techniques in modern statistics (Koenker and Bassett, 1978). In contrast to traditional regression, quantile regression looks at different quantiles of the conditional distribution instead of looking at the conditional mean curve. This approach is particularly useful for analysing the tail behaviour of the conditional distribution of climate variables.

Considering independent random variables $\{\varepsilon_t\}_{j=1}^{n}$, the model can be presented as:

$$Y_j = l(j) + \varepsilon_j, \qquad (8)$$

where the qth quantile of the distribuiton of ε_j is 0, and $l(j)$ is the qth quantile of Y_j. The nonparametric estimation for a fixed point $s(1 \le i \le n)$ is calculated as:

$$\hat{l}(i) = argmin_{l(i)}(1-q)\sum_{j=1}(l(i)-Y_j)I(l(i) > Y_j)w_j - q\sum_{j=1}(Y_j - l(i))I(l(i) \le Y_j)w_j, \qquad (9)$$

where $I(.)$ is the indicator function, $w_j = K(\frac{j-i}{h})$ with $K(.)$ as a kernel function (e.g. Gaussian Kernel), and h is a bandwidth.

The confidence band estimation follows Härdle and Song (2010) and can be presented as following:

$$\hat{l}(j) \pm (nh)^{-1/2}\{d_n + c(\rho)(2\delta \log n)^{-1/2}\}\hat{\lambda}(j), \qquad (10)$$

where ρ is the significance level. d_n, $\hat{\lambda}(j)$ and $c(\rho)$ are constants related to the kernel and the conditional distribution. The confidence band around a nonparametric estimator can be used for testing the functional form of an estimator.

3 Description of Data and Specification of Weather Indices

We apply the tests to weather data at three locations: Taipei (Taiwan), Berlin (Germany) and Mason (Iowa, USA). These weather stations have been selected for two reasons. First, they are located in different agro-ecological environments and thus it can be expected to find different weather patterns over time. Second, the quality of the weather records is good in terms of length and completeness of the data. Temperature and precipitation observations are available for the years 1910-2008 in Taipei, 1948-2010 in Berlin and 1905-2010 in Mason. The mean substitution method is used to fill occasionally missing values in the datasets.

Four weather indices are calculated from the daily observations, which capture different kinds of risk for agricultural production. The first index is the Growing Degree Days (GDD) index, which is frequently used to measure the risk of insufficient temperatures during the vegetation season (World Bank, 2005):

$$GDD = \sum_{j=b}^{d} \max\{(T_{\max,j} + T_{\min,j})/2 - T_{\mathbf{base}}, 0\}, \qquad (11)$$

where $T_{\max,j}$ and $T_{\min,j}$ denote maximum and minimum daily temperature and $T_{\mathbf{base}}$ represents the temperature that triggers plant growth. We set this parameter to 5°C. b and d denote the beginning (March 1st) and the end (October 31st) of the vegetation season, respectively. The rationale of the GDD is that plant growth (and hence yields) is proportional to temperature above the threshold $T_{\mathbf{base}}$. Another temperature related index is the Frost Days Index (FDI):

$$FDI = \sum_{j=b}^{d} \mathbf{1}\{T_j < 0\} \qquad (12)$$

where $\mathbf{1}\{.\}$ is the indicator function, which counts the number of days when temperature is below zero. The FDI takes into account the risk associated with frost on the beginning of the vegetation period, e.g. frost during the flowering period.

To capture drought risk in agricultural production we use the Cumulative Rainfall Index (CRI), which is defined as:

$$CRI = \sum_{j=k}^{m} R_j, \qquad (13)$$

where R_j denotes daily rainfall, and *k* and *m* are the beginning and end of the accumulation period. The CRI is usually defined on a monthly basis. We restrict our analysis to May since precipitation shortfalls are most harmful in this month. Bad yields, however, may also result from excessive rainfall. This kind of weather risk can be measured with the Potential Flood Indicator (PFI) (Frich et al., 2002):

$$PFI = \max_{\tau \in \{1,\ldots,365-s+1\}} \left(\sum_{j=\tau}^{s+\tau-1} R_j \right), \qquad (14)$$

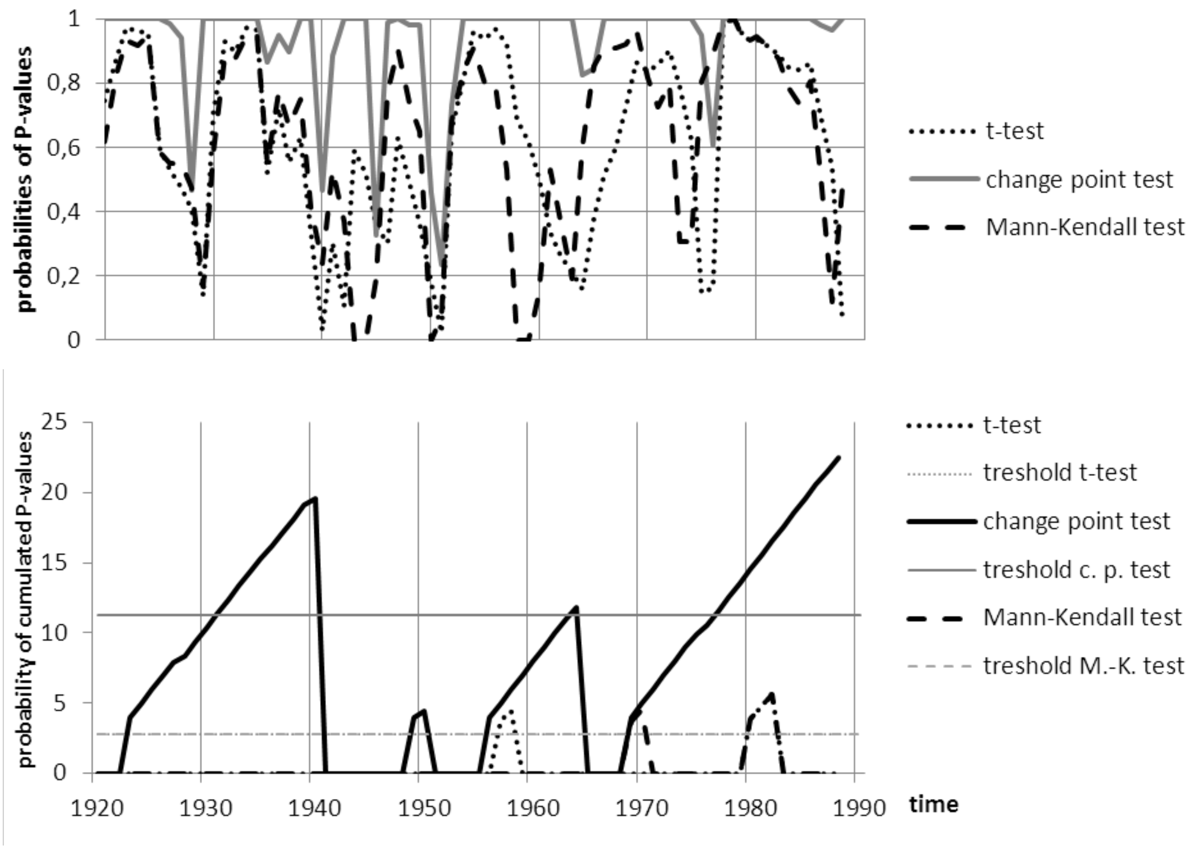
The PFI measures rainfall in the wettest *s*-day-period of the year. Following usual convention we set *s* to 5 days.

4 Empirical Results

4.1 Local trend tests

Fig. 1 illustrates the results of the local *t*-test, change point test and Mann-Kendall test for the GDD in Mason. The upper panel in Fig. 1 depicts the plot of 1- P-values of the local tests over consecutive windows of 20 observations (years). The year on the x-axis indicates the beginning of a 20-years-window. The last window, for example, starts in 1990 and covers the time period until 2010. The lower panel presents the accumulated P-values for the same time period. Summation starts if there are more than τ consecutive windows with significant P-value ($P<0.05$). The threshold values for the different tests are represented by horizontal lines. We reject the null hypothesis of no trend (or no change point) unless the cumulative values in the lower panel cross the threshold values of the respective test. The change point test, for example, indicates significant jumps in the level of the GDD in Mason during the period 1932-1941, in the year 1965 and from 1978 until 2009. The direction of the change can be identified by means of the sign of the slope parameter (β) in case of *t*-test and the sign of $\hat{\mu}_1 - \hat{\mu}_2$ in case of the change point test. The tests are conducted for all indices at all three weather stations with the exception of the FDI in Taipei, since no frost occurs in this region.

Figure 1. Local test results for GDD in Mason



The results of the GDD and the FDI are summarized in Table 1. The second column reports the beginning and the end of the time period, in which a change of a weather risk indicator appears to be significant. To be precise, "From" indicates the beginning of the first 20-years-window showing a significant change in the mean of the risk indicator and "To" means the beginning of the last 20-years-window, until which this change continues.

Apparently, the detected changes differ in their duration, as well as in their direction. In some cases there are only a few consecutive windows where a change appears to be significant while other changes are more persistent. In particular, we find a clear positive trend for the GDD in Berlin detected by all tests during different periods. Note that a positive trend of the GDD indicates more favourable temperature conditions for agricultural production. The development of the GDD is less clear in Taipei and Mason since positive and negative changes occur during the observation period. A positive trend of the FDI in Mason indicates increasing frost risk in this area whereas no such tendency can be found for Berlin.

Table 1. Trends of temperature indices

City / Indices	GDD				FDI			
	From	To	Sign	Test	From	To	Sign	Test
Taipei	1939	1949	+	C,T,M	n.a.	n.a.	n.a.	n.a.
	1959	1960	-	C				
	1981	2008	+	C				
Mason	1932	1941	-	C	1986	1987	+	T
	1958	1959	-	T				
	1965	1965	+	C				
	1970	1971	+	M				
	1978	2009	-	C				
	1981	1983	-	M,T				
Berlin	1977	1982	+	T	none	none	none	none
	1979	2009	+	C				
	1988	1989	+	M,T				

C = change point test, M = Mann-Kendall Test, T = t-test

The test results for the two rainfall based indices are summarized in Table 2. There is a clear positive trend in the CRI in Berlin indicating a reduced risk of water shortage in May. A significant positive jump of CRI can also be observed in Taipei. In contrast, several positive and negative changes of the CRI occur in Mason. It is also difficult to make a clear statement on the risk of excessive rainfall. We find several positive jumps between 1928 and 1971 in Mason. This increase of risk, however, is partially compensated by a negative change of the PFI in the late seventies. No change in the risk of excessive rainfall was detected for Berlin. Note that all changes of the CRI and the PFI are solely reported by the change point test and not confirmed by any other test.

Table 2. Trends of precipitation indices

City / Indices	CRI				PFI			
	From	To	Sign	Test	From	To	Sign	Test
Taipei	1953	1966	+	C	1949	1959	-	C
					1960	1965	+	C
Mason	1928	1933	+	C	1928	1929	+	C
	1939	1939	-	C	1961	1964	+	C
	1948	1950	+	C	1968	1971	+	C
	1988	1989	+	C	1977	1980	-	C
Berlin	1956	1958	+	C	none	none	none	none
	1963	1966	+	C				

C = change point test, M = Mann-Kendall Test, T = t-test

The results presented above show that the four risk indicators follow different trends. Moreover, their development is region specific. From tables 1 and 2 it is also apparent that the sensitivity of the test procedures differs. The change point test detects changes more often than the t-test and the Mann-Kendall test.

4.2 Quantile regressions

We now turn to the results of the quantile regression, which complement the information provided in the previous section. Instead of considering changes in the mean of weather (risk) indicators we now focus on changes in the tails of their distribution function. Fig. 2 illustrates the results for the CRI in Mason (left panel) and Berlin (right panel). The bold line represents the 10% quantile (i.e. the downside risk of rainfall) and the two thin lines show the corresponding confidence bands. The confidence bands can be employed for testing the significance of changes of the quantile over time. This can be done by checking whether a linear line with positive or negative slope fits into the corridor. For example, inspection of the left panel in Fig. 2 shows that the 10% quantile of the CRI exhibits a positive trend in Mason since 1990, which indicates a declining probability of rainfall shortfalls in May. In contrast, we observe a decline of the 10% quantile of the CRI in Berlin during the seventies and eighties as well as in the last decade. This finding seems to contradict the results of the local test of the previous section where no significant change in mean value of the CRI has been detected. One should recall, however, that the subjects of the two statistical procedures are not the same.

Figure 2. 10% Quantiles of CRI in Mason and in Berlin with confidence bands

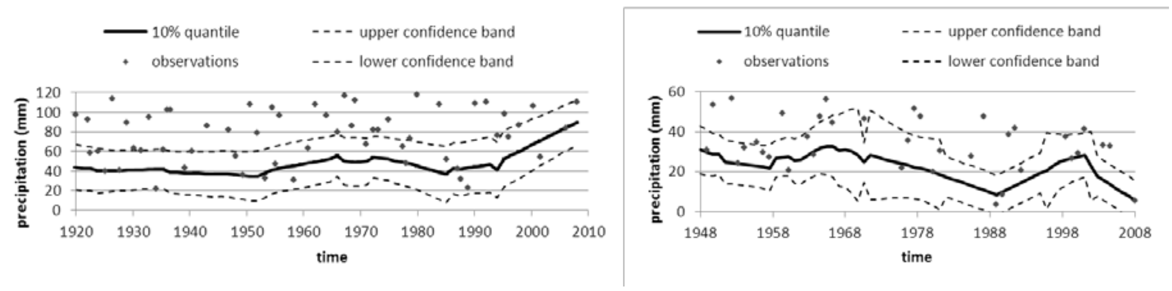


Table 3. Summary of changes of quantiles

City / Indices	GDD (10%)	FDI (90%)	CRI (10%)	PFI (90%)
Taipei	+	n.a.	-	no change
Mason	no change	-	+	+
Berlin	- +	-	-	no change

The results of the quantile regression for all weather indices and weather stations are reported in Table 3. All in all we find mixed evidence for the increasing-weather-risk-hypothesis. The 10% quantile of the GDD exhibits a positive trend in Taipei and no change can be observed in Mason GDD. We neither found evidence for increasing frost risk. There is a significant increase in the 90% quantile of the PFI in Mason, which confirms the results of the local mean test. This trend, however, does not exist in the other two cities. The 10% of the CRI tends to decline in Berlin and Taipei. This can be interpreted as an increasing exposure to drought risk at least in Berlin, since the level of rainfall is rather low in that region.

5 Conclusions

We have applied different statistical tests to analyse the presence of trends in weather indices, which are relevant to agriculture and capture the production risk in this sector. We have selected three weather stations located in Europe, Asia and North America to investigate the dynamics of weather risk indicators in different climatic zones. The results confirm our conjecture that a general trend of increasing weather risk cannot be identified.

The analysis reveals that different weather risk indicators show different pattern over time. Moreover, the changes of the weather indices are also location specific. For example, we reveal declining temperature related risk (e.g. GDD) in Taipei and Berlin but increasing temperature risk in Mason. Another feature of weather risk is that indices rarely follow long lasting trends but exhibit local jumps, sometimes in opposite direction. We also found that the test results are affected by the chosen statistical test. As a general conclusion we recommend to be specific when stating that weather risk increases under climate change. This refers to the type of risk, geographical location, time and duration of risk changes as well as the test procedure.

The analysis presented here can be extended in several directions. It would be worth to apply the test procedures to other regions and other weather events. This would allow for a generalization of the results reported here. Moreover, it would be interesting to test for trends in basic weather variables, like daily temperatures and daily precipitation and analyse if and how changes in the volatility of these variables translate into indices that directly measure the risk exposure for producers in various sectors. Finally, the power and the robustness of the statistical test procedures deserve further attention. Simulation experiments could be helpful to find out, which kind of test is most appropriate for identifying increasing weather risk.

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This research was supported by the Deutsche Forschungsgemeinschaft through the SFB 649 "Economic Risk".

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