The Trajectory of Psycho-Social Depression in Ukraine following the Chornobyl Nuclear Accident

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- P.I. RoseMarie Perez-Foster Ph.D. Administrative coordinator, psychological questionnaire construction, as well as coordinator of instrument translation and back-translation (41), (42), (43).
- Remi Frazier, M.S. Radiation dose reconstruction and analysis.
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Introduction: Nomenclature of psychosocial depression

- a sample average of self-reported psychological depression.: psycho-social depression.
- Standard composite depression inventories are not amenable to retrospective reconstruction. People cannot recall all of their specific items (e.g., appetite) years later.

  the Beck has 21 self-reported items, Hamilton 17, CESD 20, BSI 9 for its depression sub-scale.
- Attempted application of inventories would result in too many missing values.

Classification of catastrophic nuclear incidents and impacts

1. Catastrophic nuclear incidents
   1.1 Accidental– nuclear reactor malfunctions, improper disposal of medical instruments.
   1.2 Intentional– detonation of nuclear weapons, radiation dispersal devices, or improvised nuclear devices.
2. Impacts can be severe, serious or incidental, depend upon proximity to the incident.
   2.1 Severe : Radius of several kilometers. Extreme heat, damaging blast, and exposure to high levels of radiation.
   2.2 Serious: Exclusion zone can have a radius of 30- 50 km.
   2.3 Incidental: Low levels of radioactivity can be identified above naturally occurring sources. Global in extent and can last for decades.

The nuclear accident at Chornobyl as exemplar

- The most severe accident in the history of the nuclear power industry.
- Release of radioactive debris expelled at initial thermal explosions and for the next 10 days during the ensuing graphite fires.
- Approximately 10^{17} Bq of ^{137}Caesium (^{137}Cs) was released. For comparison, this fallout is 10% of that released from all atmospheric nuclear weapons tests and about 10 times the fallout of Fukushima (13).
- Our focus: Implications for extended effects of radiation dispersal device detonation.

Reactor four after accident

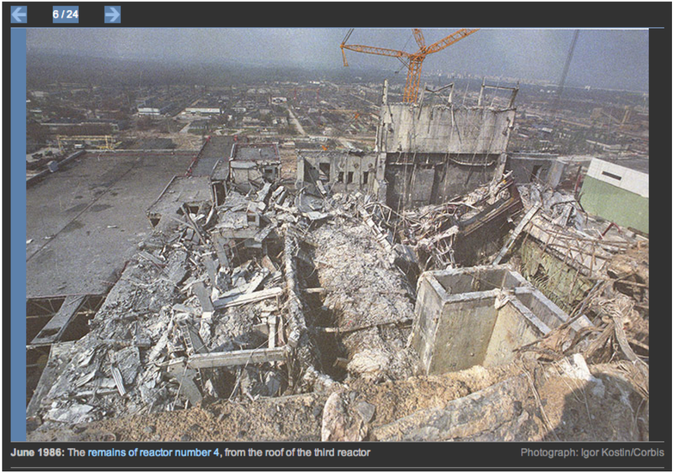


Figure 1: *Reactor four after explosion*

Devastated reactor at Chornobyl nuclear plant with Dnieper River in background

Figure 2: *Chornobyl accident site after explosions and meltdown- April 26, 1986*

Dispersal and deposition of fallout

- Long duration of the release and changing meteorological conditions dispersed radioactivity in many directions.
- Largest concentrations of radioactivity deposited in Belarus, Ukraine and the Russian Federation.
- The patterns over much of Europe were irregular with Hot Spots adjacent to Cold Spots.
- Measurements were compiled into maps in the *Atlas of Cesium Deposition on Europe following the Chernobyl Accident* published by the European Commission (13).

^{137}Caesium deposition in Ukraine

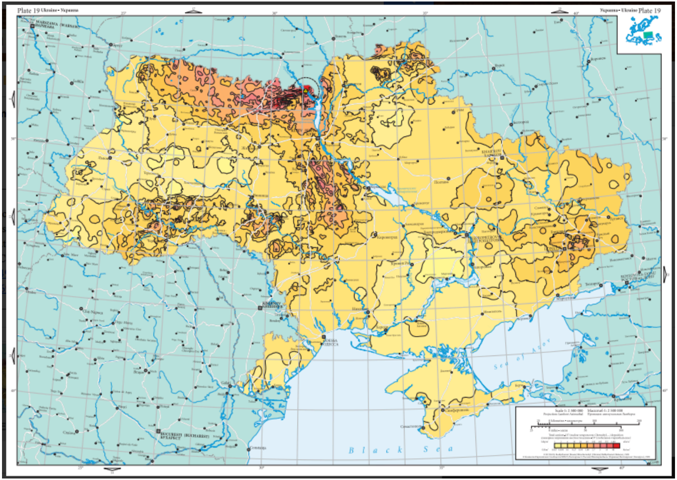


Figure 3: *^{137}Caesium in Ukraine - DeCort et al., 1998*

Thematic map of the dispersal and distribution of ^{137}Cesium

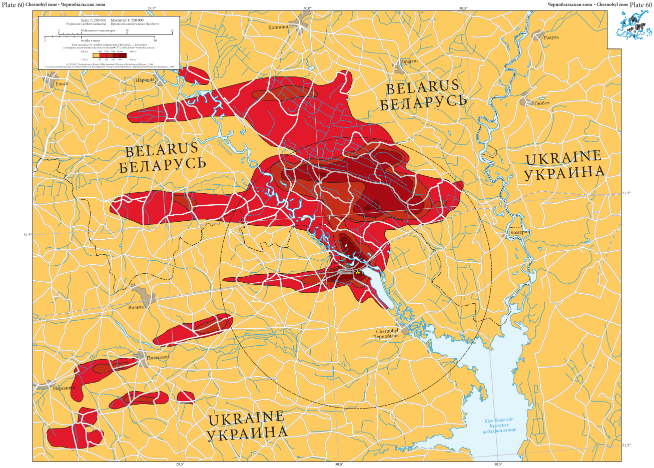


***Figure 4:** Atlas of ^{137}Cesium deposition on Europe after the Chornobyl Accident (DeCort et. al.(1998) (13))*

Literature review

- Almost all earlier Chornobyl studies were epidemiological observational studies
- Focused on highly exposed groups -
- Havenaar and van den Brink (1997) : most Chornobyl articles lacked adequate sampling protocol specification (26, 365)
- Only Ukraine World Mental Health Survey (Bromet, EJ, Gluzman, SE, Paniotto, VI, Havenaar, JM, and Gutkovich, Z, 2004) attempted to apply standard composite diagnostic interview scales to national sample, (7, 681-684).
- Bromet et al. (2011) 25 year review of Chornobyl literature, noted only 1 gerontological study attempting to use a random sampled control group.
- But these 2 studies were cross-sectional.

The Chornobyl literature in review

1. The Chernobyl Forum Report of the 20th anniversary of the Chernobyl accident : the most significant public health consequences were social-psychological (8).
2. In their 25 year review of the consequences of the Chornobyl accident, Bromet, Havenaar, and Guey (2011) : evacuees were disrupted by social uprooting, relocation, social discrimination, and stigmatization (9, 297-298).
3. Bromet et al. (2011) claim that it is almost impossible to disentangle from the general turmoil that followed the collapse of the Soviet Union in 1991.

Madigan, D. et al (2013) found that observational studies without random sampling often fail to match experimental and control groups for accurate analysis

- They attempt to overcome confounding with unadjusted incidence rate ratios,
- with age-by-gender stratification,
- with high- dimensional propensity score matching,
- or by controlling for exposure time.

Such observational studies fail to remove systemic bias

- Madigan, D. , Schuemie, M.J., and Ryan, P.B., Drug Safety, 2013, S73-82: identified systemic errors in observational studies: "... selection bias, misclassification, and residual confounding, resulting in spurious significance assessments (Observational Medical Outcomes Partnership web site: http://omop.org).
- In medical product observational studies, 54% of the studies that claimed $p < 0.05$ were not statistically significant.
- Without specific correction for such systematic error, these biases are believed to be "intrinsic to observational studies in general (48, 209,210,216)."
- Randomized neutralization of bias and the external validity of such observational studies remain in question (25).

What we propose that is different

1. We apply structural time series analysis for the first time to these data for the purposes of hypothesis testing and trajectory forecasting.
2. We use a random sample to focus on the depression symptoms reported by the general populace in the two oblasts under consideration.
3. Statistical controls for analysis.
4. A method of circumventing principal confounding end-effects with scenario of reverting to a different point of forecast origin to circumvent potentially confounding impacts of events.
5. We forecast over a horizon and evaluate the accuracy of our forecasts to demonstrate the efficacy of this method.

Potentially confounding events from 2006 through 2010

- 2006 trade dispute resulted in natural gas cut-off for 4 days.
- 2006-2007 Much political conflict and administrative instability.
- 2009 Jan 1 natural gas cut-off for 21 days
- 2008-2010 Great global recession: Steel demand declines and currency value drops

Research Objectives

1. To empirically test whether the dose to individuals from external sources of ionizing radiation released during the accident was a significant variable in predicting the temporal pattern of psycho-social depression in the population residing in the Ukrainian oblasts of Kiev and Zhitomyr.
2. To empirically test whether the perceived health risk associated with radiation from the Chernobyl accident was a significant variable in predicting the trajectory of psycho-social depression in that population.
3. To build a state space time series model to forecast the level of psycho-social depression after a nuclear incident.
4. To validate the model by misspecification testing, and to apply *ex post* and *ex ante* forecast evaluation to assess its accuracy.
5. To circumvent the potentially confounding impacts of major intervening variables at the end of the psycho-social depression series.

Survey design

- Representative sampling with a randomized telephone survey in Kiev and Zhitomyr oblasts.
- Random digit dialing: Computer generated random numbers were attached to Ukrainian area codes to form phone numbers. One person per household was interviewed.
- four callbacks at different times of day were tried.
- Pilot study of 100 separate respondents in late 2008.
- An Independent auditing group
- After data were cleaned, datasets were personally de-identified to assure confidentiality in accordance to U.S. Heath Information Privacy Act requirements prior to analysis.

Retrospective panel

Three Post Chornobyl waves

Table 1: *Wave structure of Study*

Period	**Time span**
Prelude	1980 thru Chornobyl accident on 26 April 1986
Wave 1	Chornobyl event to end of 1986
Wave 2	1987 through end of 1996 (year of new Constitution)
Wave 3	1997 through 2009 for radiation reconstruction
	1997 through interview time for other items

Endogenous variable: Psycho-social depression

Sample average annual male and female depression level

- Retrospective respondent recall of significant changes in level of depression provided the basis for computation.
- Scale ranged from 0 to 100.
- Sample annual mean was computed from 1980 to time of interview.
- Called $\texttt{maledep}_t$ and $\texttt{femdep}_t$ for gender specific analysis.

Exogenous variables

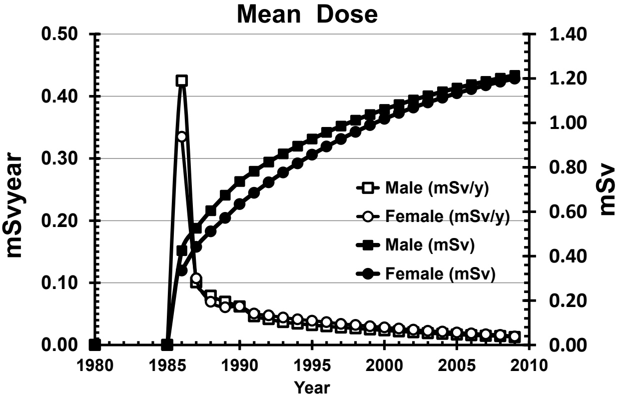
reconstructed ionizing radiation exposure risk

- Reconstructed external dose of radiation estimated in (mSv).
- This level excludes cosmic rays or voluntary medical diagnostic x-rays or treatments.
- Aggregated by year.
- Mean male cumulative dose and mean female cumulative dose were, respectively, called `mavgcumdose` and `favgcumdose`.

Exogenous variables

external exposure risk

Figure 5: *Cumulative external & differential external dose excluding natural background and voluntary medical radiation*



Exogenous variables

external dose summary measures (mSv)

In sum, the largest possible ionizing dose did not attain the level (100 mSv (National Academies of Sciences Biological Effects of Ionizing Radiation-VII) where signal could be distinguished from noise (54)

Table 2: *Summary statistics of dose from exposure to ionizing radiation*

	Ending Date		
	12/31/1986	12/31/1996	12/31/2009
Lowest value of External Dose received by an individual (mSv)	0.0074	0.036	0.047
Largest value of External Dose received by an individual (mSv)	28.0	30.0	31.0
95th Quantile of External Dose received in the sample (mSv)	0.037 - 1.4	0.14 - 3.4	0.19 – 4.4
Average value of External Dose received in the sample (mSv)	0.38	0.93	1.2
Median value of External Dose received in the sample (mSv)	0.28	0.69	0.91
Geometric Mean value of External Dose received in the sample (mSv)	0.23	0.61	0.84
Estimated Average value of External Dose from Natural Background (mSv)	0.33	5.3	12.0

Exogenous variables

Perceived Chornobyl accident-related health risk

The variables averaged in the index were

1. Percent the respondent believed Chornobyl accident affected his or her health,
2. Percent respondent believed that Chornobyl accident affected his or her family's health,
3. Percent of belief in the statement that in Kiev/Zhitomyr oblasts, most human cancer cases are known to be caused by radiation, was a reflection of regional risk.
4. Their scale Cronbach α reliability coefficient exceeded the recommended threshold of 0.70 for scale inclusion. All male alphas were larger than 0.82 and all female alphas were 0.76 or larger.

Exogenous variables

Mean number of illnesses per period

- A self-report of the average number of illnesses per wave separately for males and females.
- With gender-specific variable names
  $\texttt{millw}_t$ *and* $\texttt{fillw}_\texttt{t}$.

Figure 6: *Time series plot of key variables*

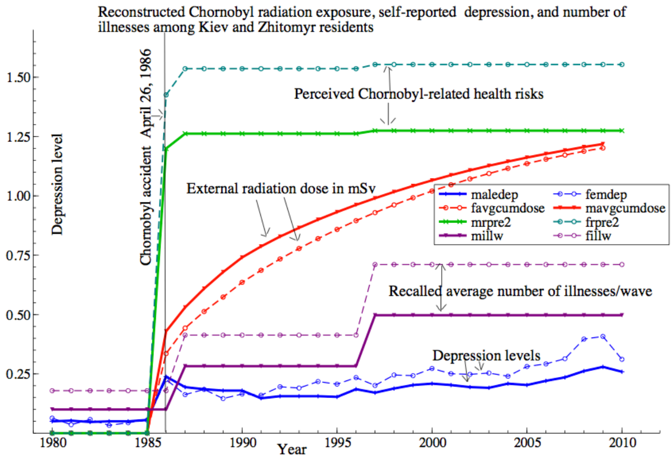


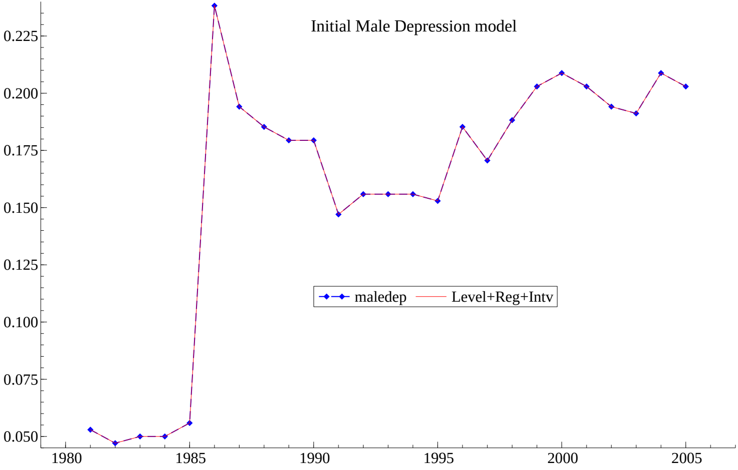
Figure 2: Cumulative external dose (excluding natural ambient and medical diagnostic or treatment radiation) and psycho-social depression in Kiev and Zhitomyr oblasts

Why state space models?

- Successfully applied to panel analysis with mixed frequency data (20, 2-3).
- Augmented Kalman filter permits analysis of nonstationary time series (Harvey, 1989), (Durbin and Koopman, 2000).
- Easily handle missing data.
- Their smoothing capability renders them applicable to small samples.
- They allow us to test our research questions with short datasets.

Initial Male model

Figure 7: *Male depression after Chornobyl*



Initial Male model

- Unobserved components (level and slope) and predictor variables– namely, average cumulative external dose measured in mSv, perceived Chornobyl health risk, and a self-report on the mean illnesses experienced during the period under consideration.
- We used an Rd^2 in lieu of the ordinary R^2 in this case. The conventional formula applies only to stationary data, where values are bounded by the limits of 0,1. For non-stationary data, Andrew Harvey (1989) suggested using a variant that is more robust to trending data, which he calls Rd^2:

$$Rd^2 = 1 - \frac{sse}{\sum_{t=1}^{T}(\Delta y - \Delta\bar{y})^2} \tag{1}$$

- where the denominators consist of differenced terms measuring rates rather than undifferenced ones measuring levels of the endogenous variable (24, 268).

Initial Male model -continued

- Our initial male depression model contained the a local level,
- local slope,
- and an irregular component,
- mean cumulative external dose was not significant p = 0.402
- differential male age was not significant p =0.839
- n.s. items were purged from model

Final male depression model

$$
\begin{aligned}
MaleDep_t = \quad & 0.094 Level_t^{**} & + \quad & 0.002 Slope_t^{\dagger} \\
& -0.177 millw_t^{***} & + \quad & 0.152 MalePerceivedRisk_t^{***} \\
& +0.033 LevelShift\_1991_t^{**} & + \quad & 0.028 LevelShift\_1996_t^{*} + e_t
\end{aligned}
$$

- where
  $* * * = p < 0.001$
  $** = p < 0.001$
  $* = p < 0.05$
  $\# = p < .10$
  $\dagger =$ *significant at the* 0.602 *level*

- $MaleDep_t$ = male self-reported depression above 5%,
- $Level_t$ = level component,
- $Slope_t$ = slope component,
- $milllw_t$ = average number of recalled illnesses per wave,
- $MalePerceivedrisk_t$ = Male Chornobyl related perceived health risk ,
- $LevelShift\_1991_t$ = level shift at collapse of USSR, and
- $Levelshift\_1996_t$ = level shift at completion of Constitution and creation of national currency. Level shifts are event indicator dummy variables coded as 0 before the event, and 1 thereafter.

Interpretation

- Mean male cumulative external dose from ^{137}Cs did not appear to significantly predict on male psycho-social depression, so we pruned it from equation.
- The male psycho-social depression level declines in 1990 but rises in level in 1991 as the Soviet Union collapsed and 90% voted for independence in a nationwide referendum.
- Male perceived Chornobyl related health risk remained significant. The coefficient indicates a positive relationship between perceived Chornobyl related health risk and male psycho-social depression.
- Although depression increases before 1996, there is a decline in depression to a new level that is higher than the previous depression level in 1996, when a new constitution was adopted along with a new currency.
- The dominant explanatory variable is male perceived health risk. The recalled average number of illnesses per wave emerges as a statistically significant explanatory variable with a negative coefficient. Diagnosis of physical illness may allow treatment and recovery, reducing depression.

Model misspecification tests

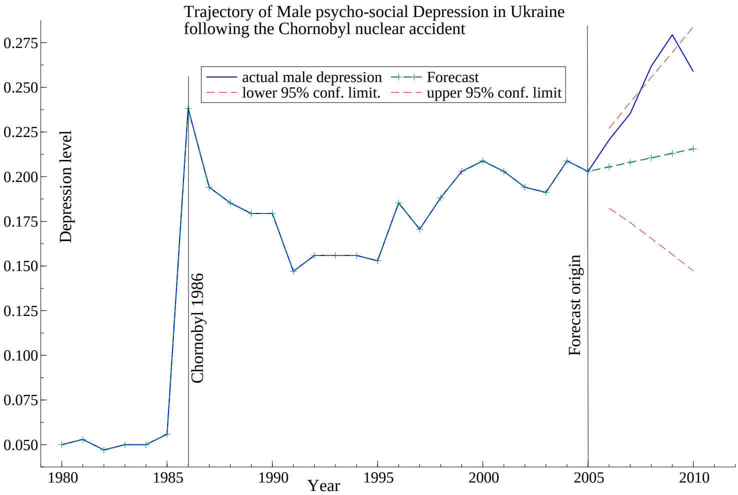
Model validation with passage of all misspecification tests

- The final male model passed all misspecification tests for residual autocorrelation, homogeneity, normality, and outlier nonsignificance.

Ex post forecast assessment

- Over 8 years of ex post forecast evaluation prior to a point of forecast origin:
- No statistically significant difference between the forecasts and the data with a χ^2 (df=8) test at the 0.05 significance level. Nor did we find that the forecast exceeded the bounds of significance for the CUSUM t- test.

Figure 8: *Ukrainian male depression forecast profile with 95% prediction confidence limits in Kiev and Zhitomyr oblasts 2005-2010*



Forecast profile

Table 3: **Male Depression Forecast profile from 2005 onward**

	Forecasts	with		95% confidence interval
Period	**Forecast**	**stand.err**	**leftbound**	**rightbound**
2006	0.20547	0.01079	0.18389	0.22705
2007	0.20800	0.01682	0.17436	0.24164
2008	0.21053	0.02253	0.16547	0.25559
2009	0.21306	0.02827	0.15652	0.26960
2010	0.21559	0.03416	0.14727	0.28391

Ex ante forecast evaluation

Table 4: **Male Depression ex ante Forecast Evaluation**

Forecast accuracy	measures	from	2005	forwards:	
Period	**Error**	**RMSE**	**RMSPE**	**MAE**	**MAPE**
2006	-0.01512	0.01512	0.68531	0.01512	6.85314
2007	-0.02729	0.02206	0.95267	0.02121	9.22639
2008	-0.05123	0.03463	1.37186	0.03121	12.67511
2009	-0.06635	0.04472	1.67966	0.04000	15.44302
2010	-0.04323	0.04443	1.67781	0.04065	15.69516

- Version 3 of Symmetric MAPE attempts to compensate for scale dependency at the smaller end of the 0 to 100 scale, where the conventional MAPE percentages become inflated. This version has more robustness to outliers than does the earler versions.

$$SMAPEv3 = \frac{\sum_{t=h-1}^{H} |F_t - A_t|}{\sum_{t=h-1}^{H} (A_t + F_t)} * 100$$

- Symmetric MAPE version 3 indicates that the overall SMAPE for males over the 5 year forecast horizon of 2005 to 2010 (plus the preceding observation being used for a starting value) for males is merely 2.96%, indicating more forecast accuracy than that indicated by the MAPE.

Findings: Initial Female Model

- The initial female model included a local level
- a local slope,
- mean cumulative female dose was not significant $p = 0.528$
- self-reported average number of illnesses per wave was not significant $p = 0.207$.
- differential log of female average age was not significant $p = 0.407$.
- level shift at 1987 was not significant $p = 0.147$.
- model could not converge and n.s. items were pruned from model.

Initial female model

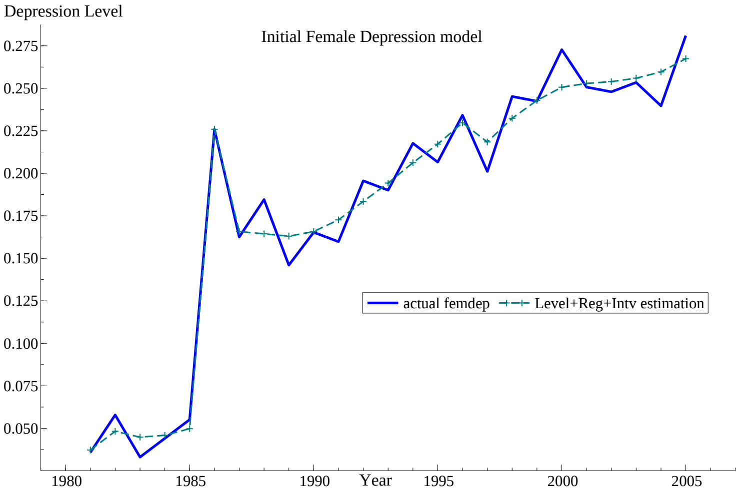


Figure 9: *Female depression after Chornobyl*

Findings: Final female depression trajectory model

$$\begin{aligned} FemDep_t = \; & 0.165 Level_t^{***} && + \; 0.005 Slope_t^{\#} \\ & +.067 FemPrcvdRisk_t^{***} && + \; 0.075 blip1986_t^{**} \\ & -0.031 blip1997_t^{\#} && + \; 0.028 blip2000_t^{\#} + e_t \end{aligned}$$

where

$\# = p < 0.10$

$* = p < 0.05$

$** = p < 0.01$

$*** = p < 0.001$

- and FemDep_t = Female reported depression, $Level_t$ = local level component, $Slope_t$ = statistically almost significant local slope component, e_t= irregular or noise component, $FemPrcvdRisk_t$ = female perceived Chornobyl related health risk. and $blip1986_t$ is a blip dummy indicator, coded as 0 when the event is not taking place and 1 during the occurrence of the represented event. In this equation, the outlier indicators are coded as 1 for the year indicated and zero otherwise.
- When we examine the final female model, we observe that the largest effect appears to be that of the time-varying level. The second largest coefficient is that of the 1986 spike in depression ($blip\_1986_t$) at the time of the Chornobyl accident. Almost as great as this impact is that of the female perceived risk of exposure to radioactivity from radiation released from the Chornobyl event. It is noteworthy that female cumulative external dose of ionizing radiation exposure is not a significant predictor of reported female depression in this model. The negative coefficient of the 1997 outlier may express establishment of the democratic Constitution in 1996, the establishment of the national currency, and the signing of the Ukrainian-Russian friendship pact in 1997.

Misspecification tests

Model validation with passage of almost all tests

- No significant residual heteroskedasticity.
- No significant residual non-normality
- All residual diagnostic tests passed at a significance level of .05 with the exception of a significant lag 3 autocorrelation.
- However, the Kalman filter algorithm appeared to correct for this because it made no difference with the ex post forecast evaluation.

Female ex post forecast evaluation

- Failure Chi2(7) test is 4.315 with a p-value > 0.7.
- Cusum t(7) test is -0.310 with a p-value > 0.10.

Female depression trajectory forecast profile

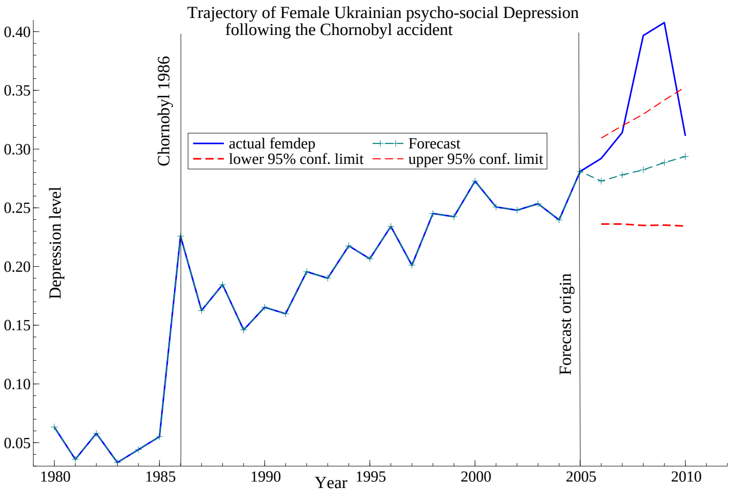


Figure 10: *Female depression Forecast profile from 2005 over a five year horizon*

Table 5: Female Depression Forecast profile from 2005 onward

Forecasts	with 95%	confidence interval	from	2005 forwards:
Period	Forecast	stand.err	leftbound	rightbound
2006	0.27277	0.01829	0.25450	0.29109
2007	0.27801	0.02092	0.25711	0.29898
2008	0.28324	0.02369	0.25956	0.30702
2009	0.28847	0.02660	0.26189	0.31519
2010	0.29371	0.02962	0.26409	0.32348

Forecast evaluation

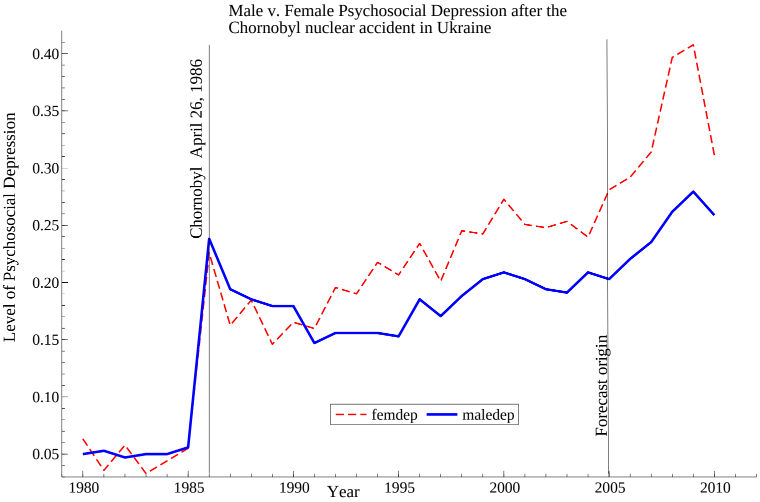
The MAE is small until we reach 2008. But it's only .056 then. It's maximum is 2009 when Russia cuts off the gas for three weeks. It goes when an agreement is reached. The MAPE jumps in 2008 but peaks at almost 19% when the gas is cut-off. The SMAPE is less than 4.73%.

Table 6: **Female Depression ex ante Forecast Evaluation**

Forecast accuracy	measures	from	2005	forwards:	
Period	**Error**	**RMSE**	**RMSPE**	**MAE**	**MAPE**
2006	-0.01924	0.01924	0.65888	0.01924	6.58882
2007	-0.03604	0.02889	0.93578	0.02764	9.03300
2008	-0.11345	0.06962	1.81942	0.05625	15.55529
2009	-0.11914	0.08479	2.14965	0.07199	18.97790
2010	-0.01759	0.07625	1.93923	0.06111	16.31214

- SMAPE v3 for the females over the five year forecast horizon is merely 4.73%.

Comparison of males and females



Conclusions

1. Dose from external radiation sources does not appear to predict psycho-social depression for either males or females.
2. Perceived health risk from Chornobyl accident is found to predict psycho-social depression for males and females.
3. State space models may be used to predict and assess post-nuclear incident psycho-social depression trajectories.
4. Recalled number of physical illnesses is significantly negatively related to psycho-social depression in males but not in females.
5. Circumvention of major confounding end-effects may be accomplished with state space forecasting from earlier points of forecast origin.
6. Significant level shifts and blips in psycho-social depression are pivotal points in Ukrainian history that warrant serious investigation for proper interpretation.

Discussion of model Validity

- Internal validity is preserved by circumvention of confounding variables by such scenario forecasting. Justified by political and economic nature of potentially confounding variables.
- Statistical conclusion validity: Power is reduced by reversion to earlier point of forecast origin. This is best done at end of series only for one or two major events. Circumvention of confounding intervening variables fortifies internal validity.
- Ex post forecast evaluation is evaluated by CUSUM and t-tests with none of the 8 preceding estimated values significantly different from the actual values, justifying further forecasting.
- External validity (Generalizability) is preserved by random selection. No problem with empirical correction for systematic bias.

Limitations

- We do not claim to be able to circumvent all, but perhaps only major potentially confounding events, at the end of this series.
- Assumption of relatively immediate mass impact, and no long time delay for impact is warranted here.
- This circumvention mechanism may not work well for potential confounders impacting early or mid-way on the series.
- This should not be applied to different types of impacts where their impacts overlap if they need to be distinguished from one another: Avoid masking or smearing events and/or impacts when these need to be distinguished from one another.
- Because we could not reliably forecast from 1989-1991,, since that point of forecast origin is too early in the series, it is possible that the collapse of the Soviet Union may not be totally circumvented.
- We cannot perform conventional Pearson criterion validation with standard diagnostic battery because this is the first time series analysis of this subject matter, and there is no previously established time series standard against which this can be compared.

Discussion - Directions for future research

- Can be applied to testing significance of historical political and economic impacts.
- For limited applications of confounding end-effect circumvention
- This method could be applied to the study of other nuclear accidents.
- It should be applied for purposes of generalization of our findings regarding Chornobyl.
- We are also beginning to model the volatility of the data generating process as well.
- Exploring application of Sir David Hendry, Jennifer Castle, and Jurgen Doornik's Impulse Indicator Saturation and Step Indicator Saturation to such modeling (16, 234), (17, 6-10).
- Exploration of Neil Ericsson's application of ultra-saturation methods with broken trends and interactions as well.
- These empirical methods may be used to identify key events that explain endogenous variables in many of the social sciences and provides the basis for a new historiography.

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Sample demographics (Kiev oblast: 85.9% , Zhitomyr oblast 14.1%)

- Age range: 28 - 84 years
- Gender composition: 48.3% *males and* 51.7% *females*
- Martial status: Single: 9.1% ; cohabiting: 4.6% ; married: 69.5% ; separated: 1.14% ; divorced: 6.98% ; widowed: 8.7%
- Employment status: full - time 61.8%; part- time: 8.12% ; retired: 24.8%; unemployed or voluntary: 5.27%.
- Occupational status: Prof, admin, exec: 26.9%; tech sales admin support: 17.2%; service: 10.6%, precision, craft prod: 6.1%; factory laborer, transp 3.3%; agricultural forestry, fishing, trapping, logging: 1.1%; homemaking or caregiving: 23.8%, student: .14%.
- Educational achievement: Not HS grad: .14%; HS grad 5.27%; tech degree 39.6%; Coll grad 13.8%; masters degree 40.0%; MD or Ph.D 1.23%.
- Income: Insufficient for basics: 23.3%; just sufficient 42.2%; sufficient + a little extra: 29.2%; affords luxury items : 3.13%.

Threshold of Human biological risk

- A recent report from the US National Academies of Sciences: Biological Effects of Ionizing Radiation (BEIR VII) summarizes the latest findings of epidemiological and experimental research on low levels of radiation. At doses less than 100 mSv, statistical limitations make it difficult to evaluate risks in humans.
- The lifetime-attributable-risk (LAR) for developing cancer in a population receiving 100mSv would be about 1% for males and 1.4% for females This is about 40 times lower than the incidence of cancer expected in the population from other causes.
- For our representative sample,median accumulated dose is about 10 times less than the external dose expected from naturally occurring background sources.

Kalman filter (34, 40)

State vector and predictive variance updating equations under NID assumptions

$$a_{t+1} = E(\alpha_t | Y_t), \qquad P_{t+1} = Cov(\alpha_{t+1} | Y_t) \tag{3}$$

$$v_t = y_t - Z_t a_t \quad (Nx1) \tag{4}$$

$$F_t = Z_t P_t Z_t' + G_t G_t' \quad (NXN) \tag{5}$$

$$K_t = (T_t P_t Z_t' + H_t G_t') F^{-1} \quad (mxN) \tag{6}$$

$$\alpha_{t+1} = T_t \alpha_t + K_t v_t \quad (mx1) \tag{7}$$

$$P_{t+1} = T_t P_t T_t' + H_t H_t' - K_t F_t K_t' \quad (mxm) \tag{8}$$

where a_{t+1} = a random mean vector (m x 1)
α_{t+1} = the latent state vector
$Y_t = y_1 \ldots y_t$ observed time series from t=1 to t=n (N x 1)
v_t = one-step ahead innovation error (N x 1) of y_t
Z_t = factor loading matrix (N x m)
P_t = variance matrix of state vector (m x m)
T_t = transition coefficient matrix (m x m)
G_t = specific error vector of measurement model (N x r)
F_t = variance of the prediction error v_t
K_t = Kalman gain
H_t = selection matrix for state errors (m x r)
n = number of observations
m = dimension of the state vector
N = number of variables

r = dimension of the disturbance vector.