

Coal, Climate Change, and Peak Oil

David Rutledge, Caltech

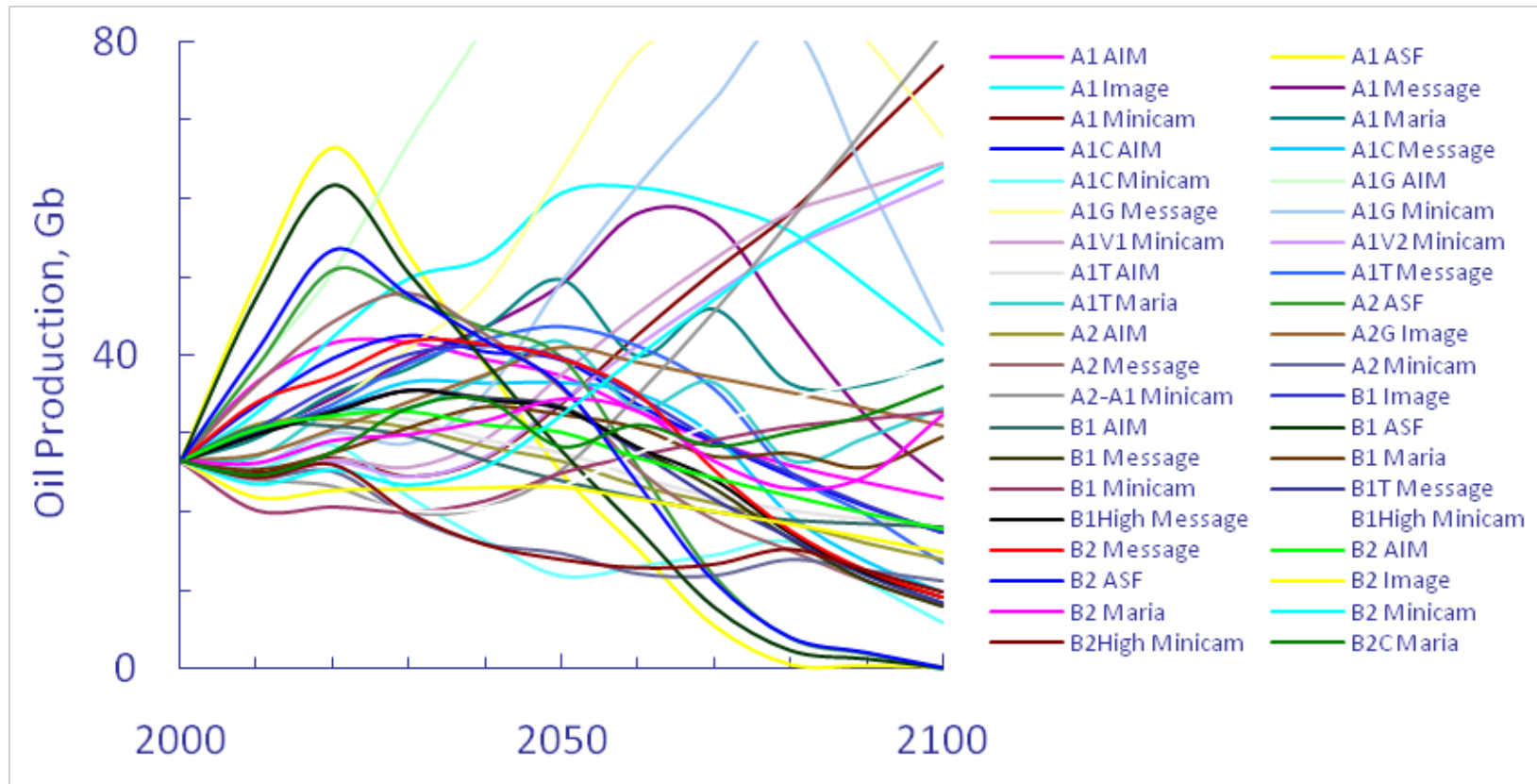
web: rutledge.caltech.edu

email: rutledge@caltech.edu

The UN Panel on Climate Change (IPCC)

- Released 4th Assessment Report in 2007
- For climate projections, the IPCC uses
 - 19 computer models with a range for temperature sensitivity for a doubling of the CO₂ level of 2.1 to 4.4°C
 - Gives a subjective 66% chance that the true sensitivity is in the range from 2.0 to 4.5°C
 - Gives a subjective 90% chance that the true sensitivity is above 1.5°C
- For oil, gas, and coal production, the IPCC works with scenarios — “... 40 SRES [Special Report on Emissions Scenarios] scenarios together encompass the current range of uncertainties...”

Oil Production in the IPCC Scenarios

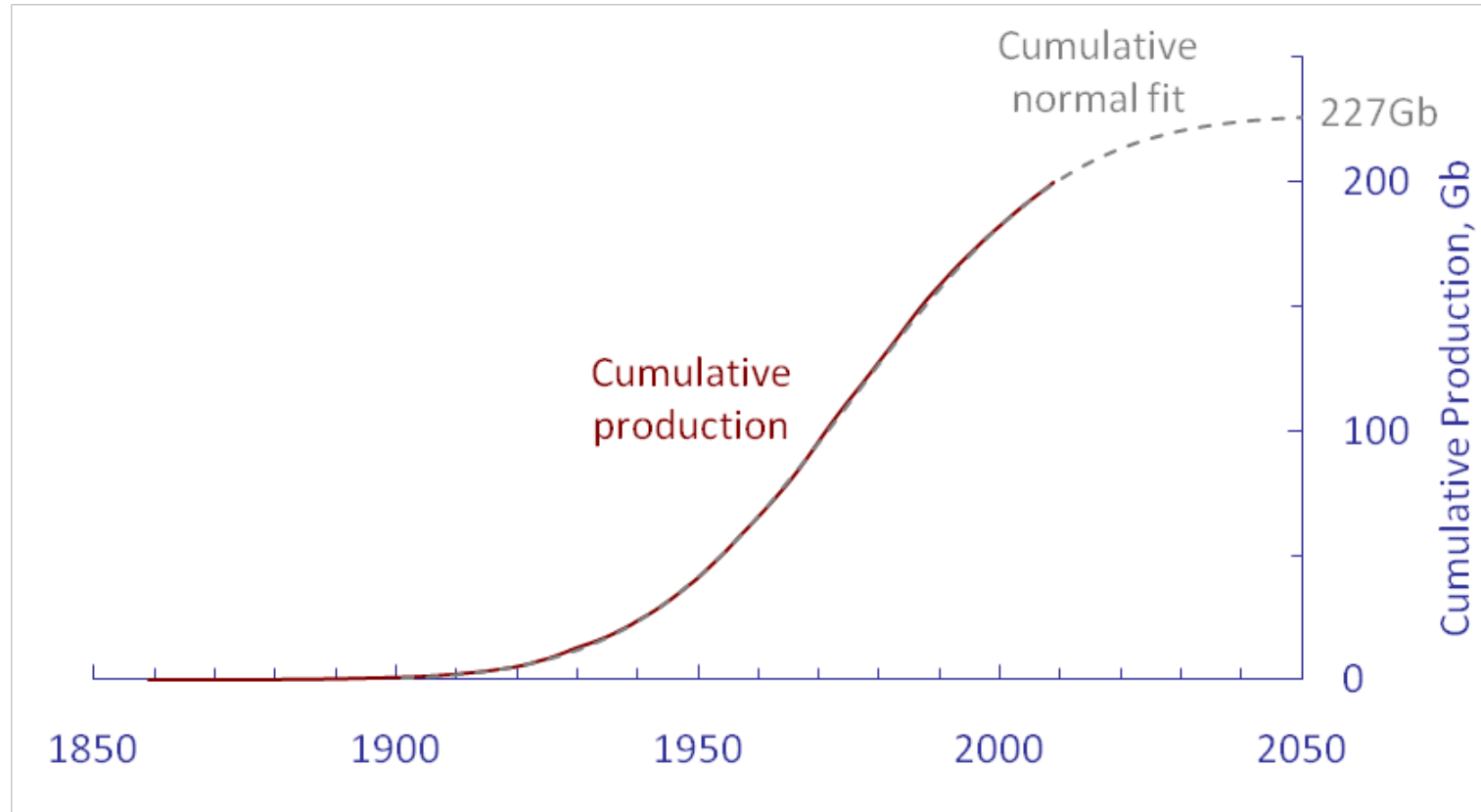


- Gb = billions of barrels
- Range for production from 2010 to 2100 is 1,446Gb to 8,278Gb — still growing in 13 scenarios in 2100

Goal is to Reduce these Uncertainties

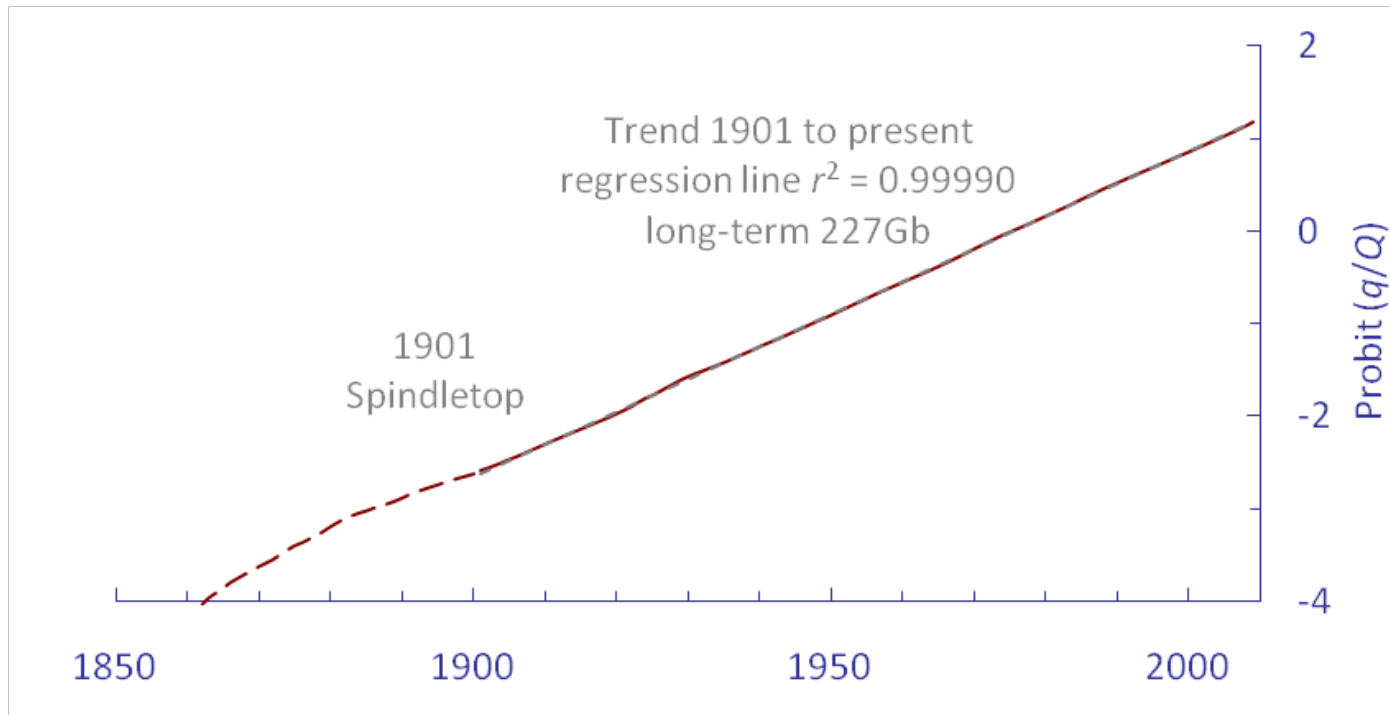
- *Residuals* are the differences between data and models
- The “best” model is used for *projections* — for linearizations, I use the model with the highest squared correlation coefficient (r^2), and for non-linear curve fits, I use the model with the lowest sum of squared residuals
- *Uncertainty* refers to the inconsistency in a group of projections
- A *range* giving the upper and lower values is one measure of uncertainty — a one-sided example would be civil engineers designing for a 100-year flood
- When residuals can be decorrelated, we can create bootstrap *replications*, which are effectively alternative histories with the same statistical properties as the actual history
- Replications allow us to calculate *confidence intervals* — statements of the form “The 90% confidence interval is 1.9°C to 2.4°C” means that there is a 90% chance that the interval includes the actual temperature
- Limitations in confidence intervals — they depend on the form of the models, some uncertainties are left out, and the models can break down (uncertainty interval might be a better term)

Cumulative Production for US Crude Oil



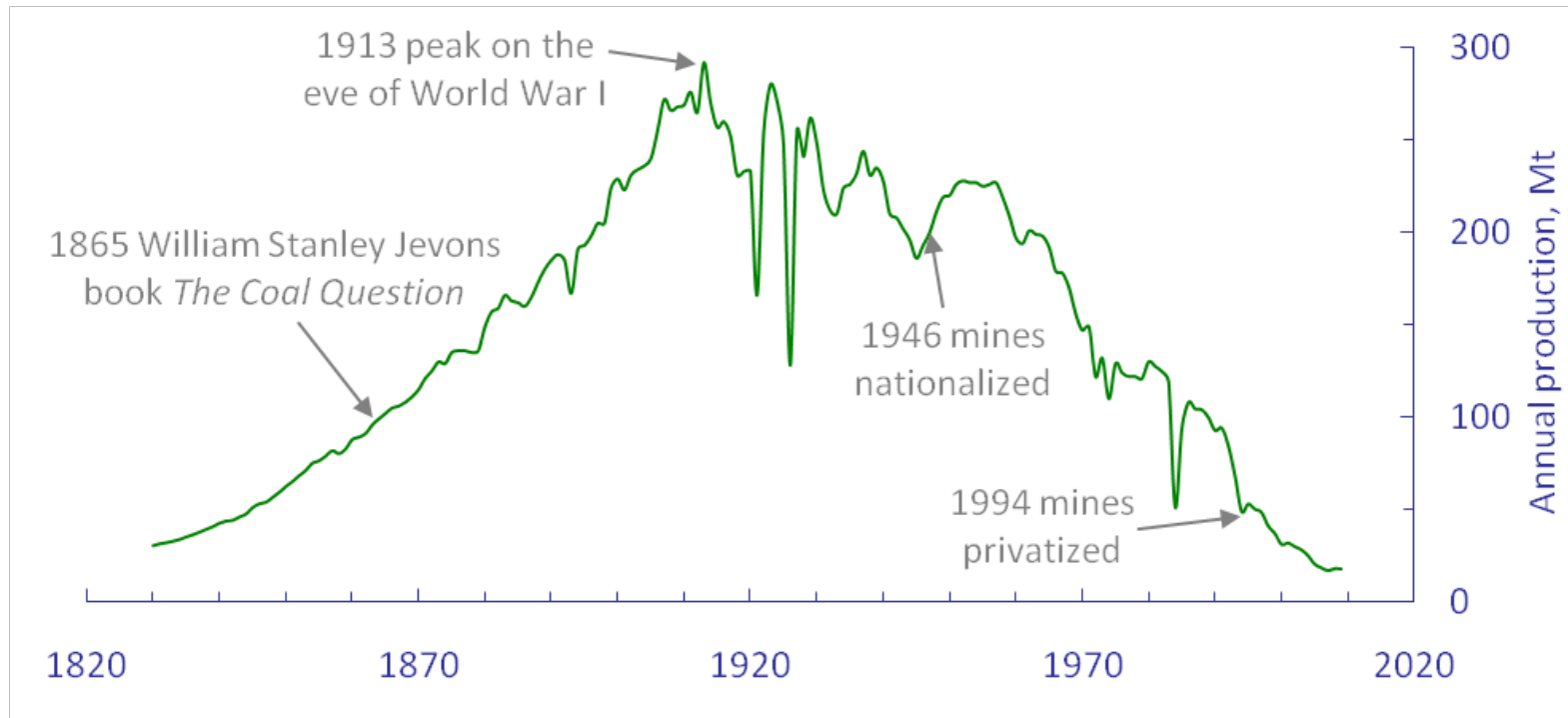
- Top of the scale for the normal gives a projection for the long-term production — total production, past and future

Probit Transform for US Crude Oil



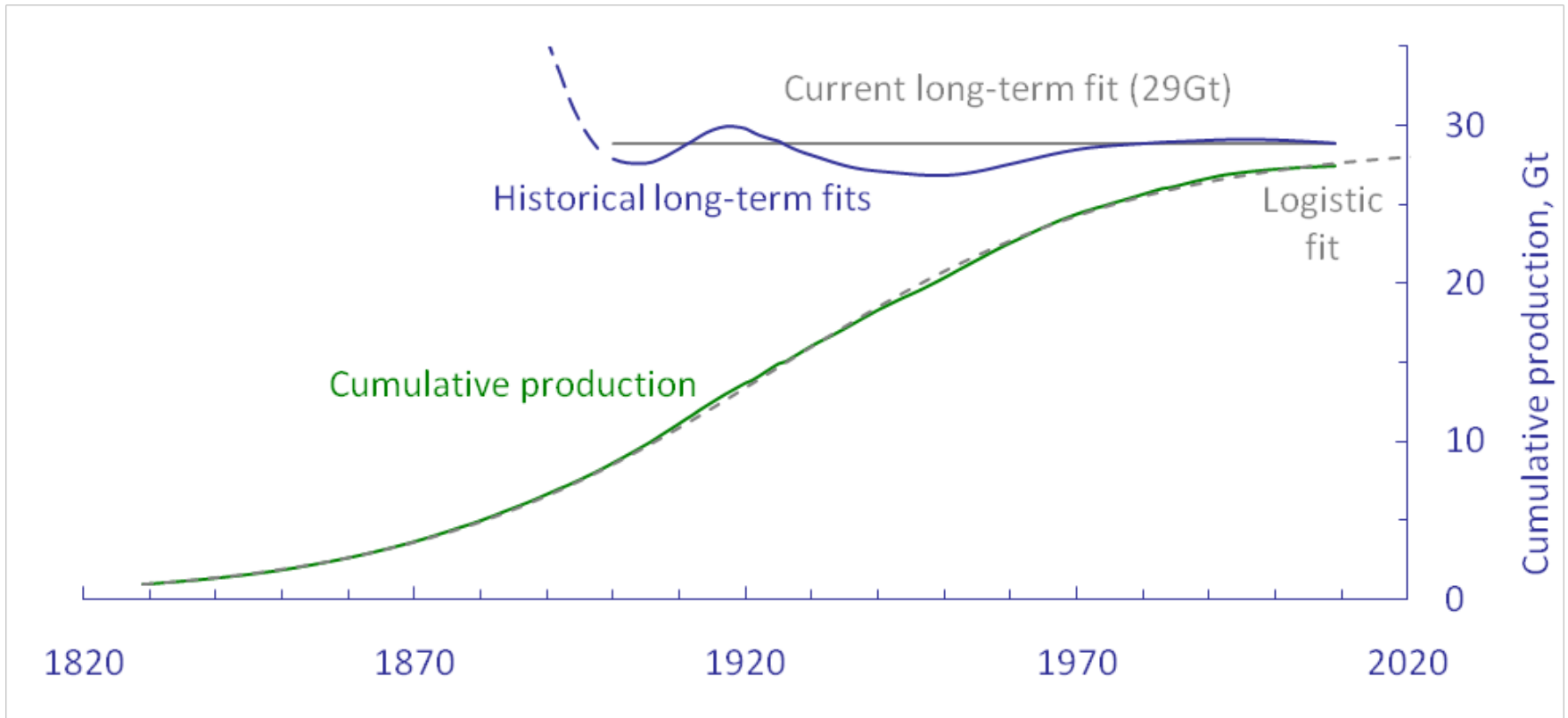
- Cumulative production is linearized by the probit transform (inverse of the standard cumulative normal)
- The plot is for $\text{probit}(q/Q)$, where q is cumulative production, and Q is the proposed long-term production
- Maximize r^2 (square of the correlation coefficient) — gives 0.99990
- A one-parameter fit, 1 second in Excel

UK Coal Production



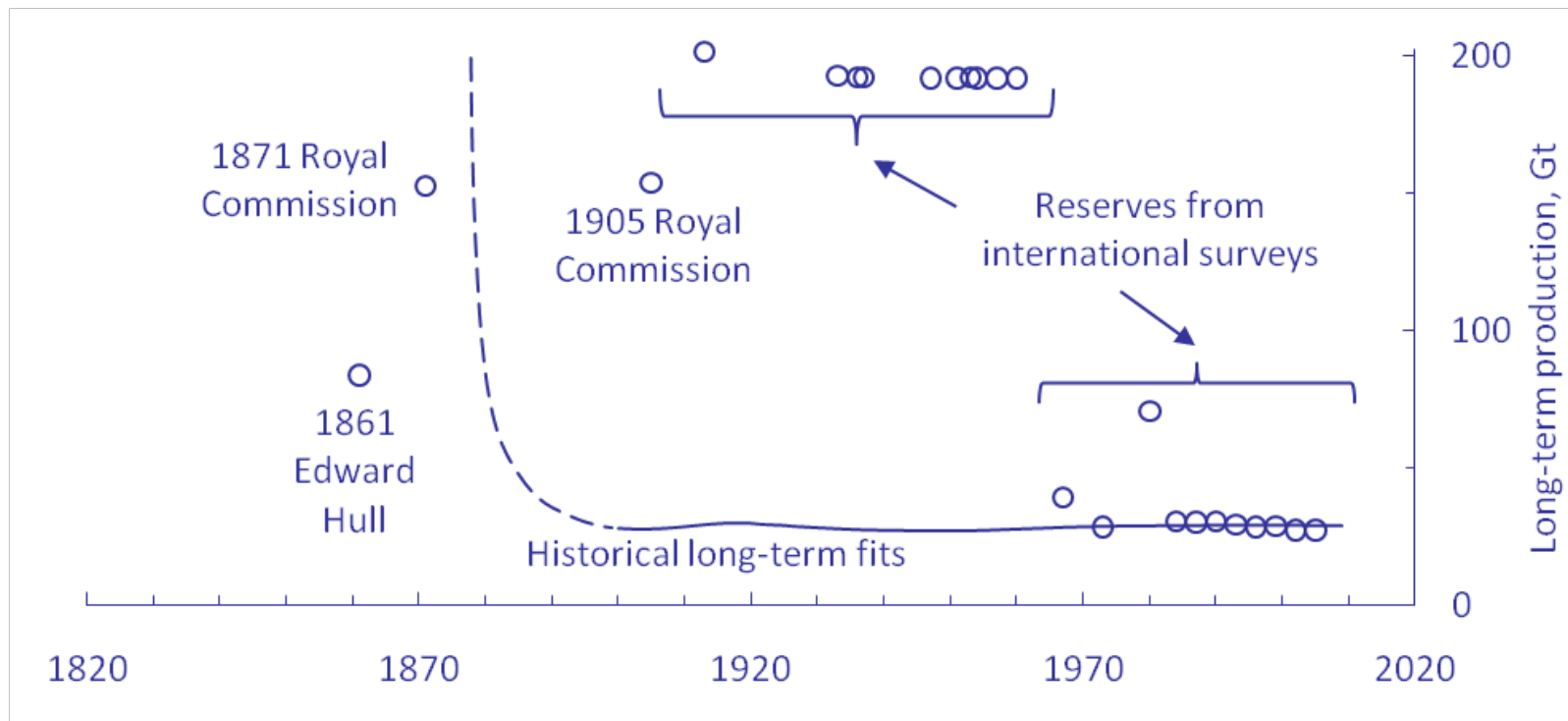
- Mt = millions of metric tons
- Production is now 16 times less than the peak — the last time the production was this low, Napoleon was alive
- In 1913, Britain exported 31% of its production, now it imports 74% of the coal it burns

Cumulative Production and Historical Fits



- Estimates for long-term production have varied in a 11% range since 1900
- Fit uses a different s-curve, the logistic function, that gives a better fit than the normal
- Linearized through the logit transform $r^2 = 0.9996$

Historical Long-term Fits Compared with Reserves



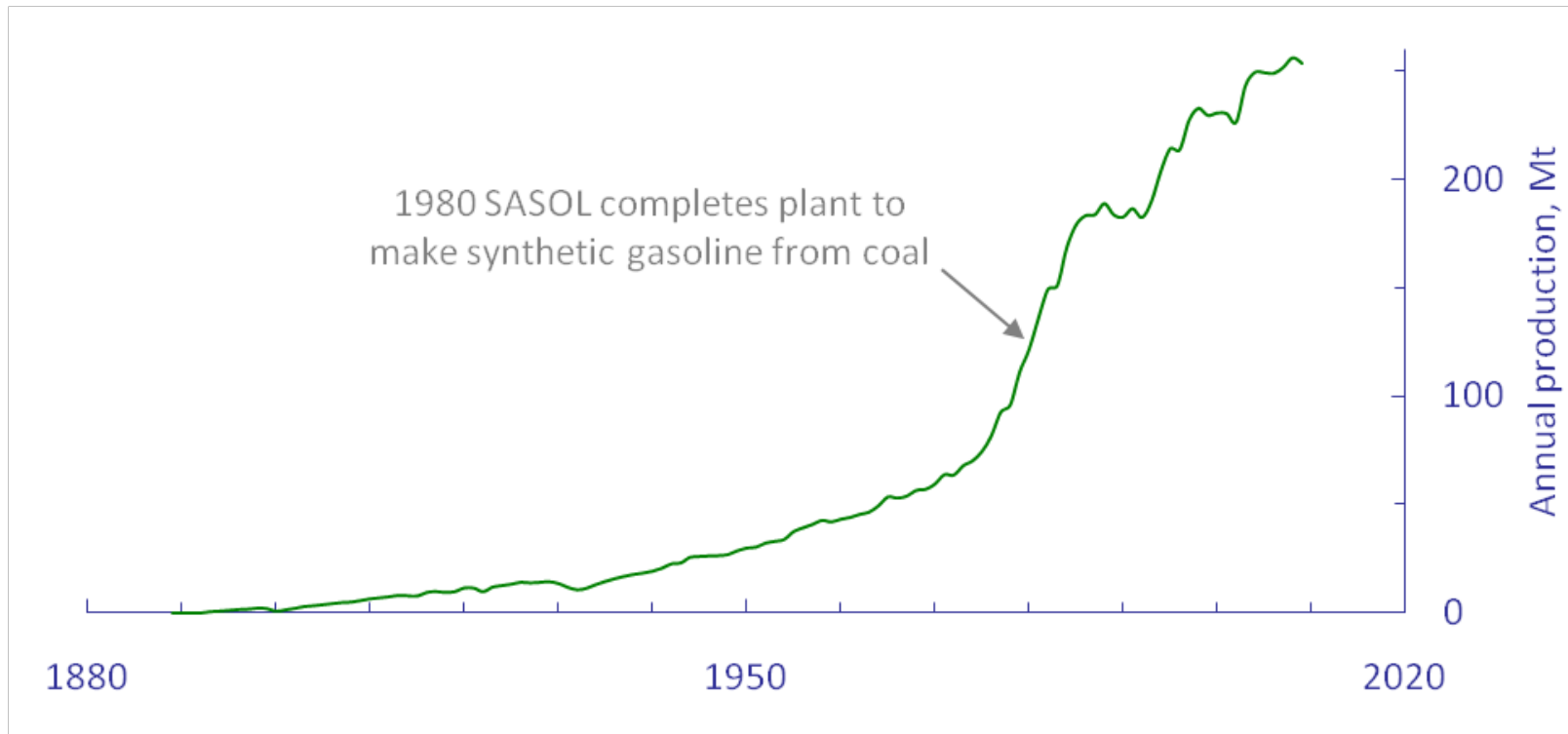
- Reserve numbers are available before long-term fits
- Produced 18% of the 1871 Royal Commission reserves + cumulative
- Criteria were too optimistic — 1-ft seams, 4,000-ft depth
- Collapse in reserves fifty years ago — the five collieries left with a producing face (down from 803 faces in 1972) are all more than fifty years old

Summary for Mature Regions

Region	Current production Mt	Cumulative production Gt	Long-term production Gt	Range Gt	Early reserves + cumulative Gt	Reserves year	Long-term fit/ (early reserves + cumulative)
United Kingdom	18	27.4	28.9	26.8 - 30.0 (11%)	153	1871	19%
Pennsylvania anthracite	1.6	5.03	5.05	3.1 - 5.1 (40%)	12	1921	42%
France and Belgium	0.2	7.2	7.6	4.3 - 8.5 (55%)	33	1936	23%
Japan and South Korea	3.8	3.6	3.7	2.5 - 3.9 (36%)	17	1936	21%

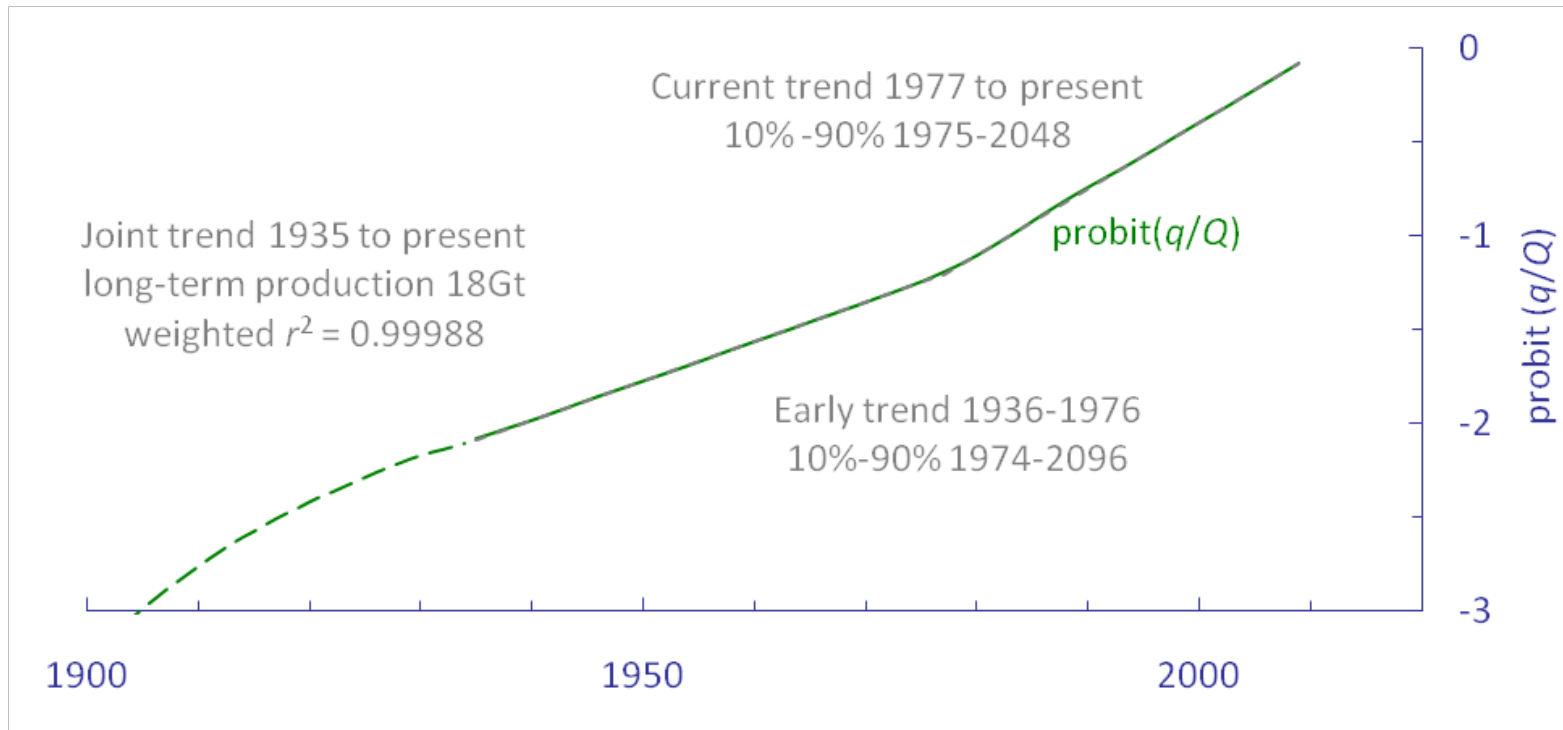
- Early reserves over-estimated minable coal by a factor of 4:1
- Average range for historical curve fits is 36%

African Coal



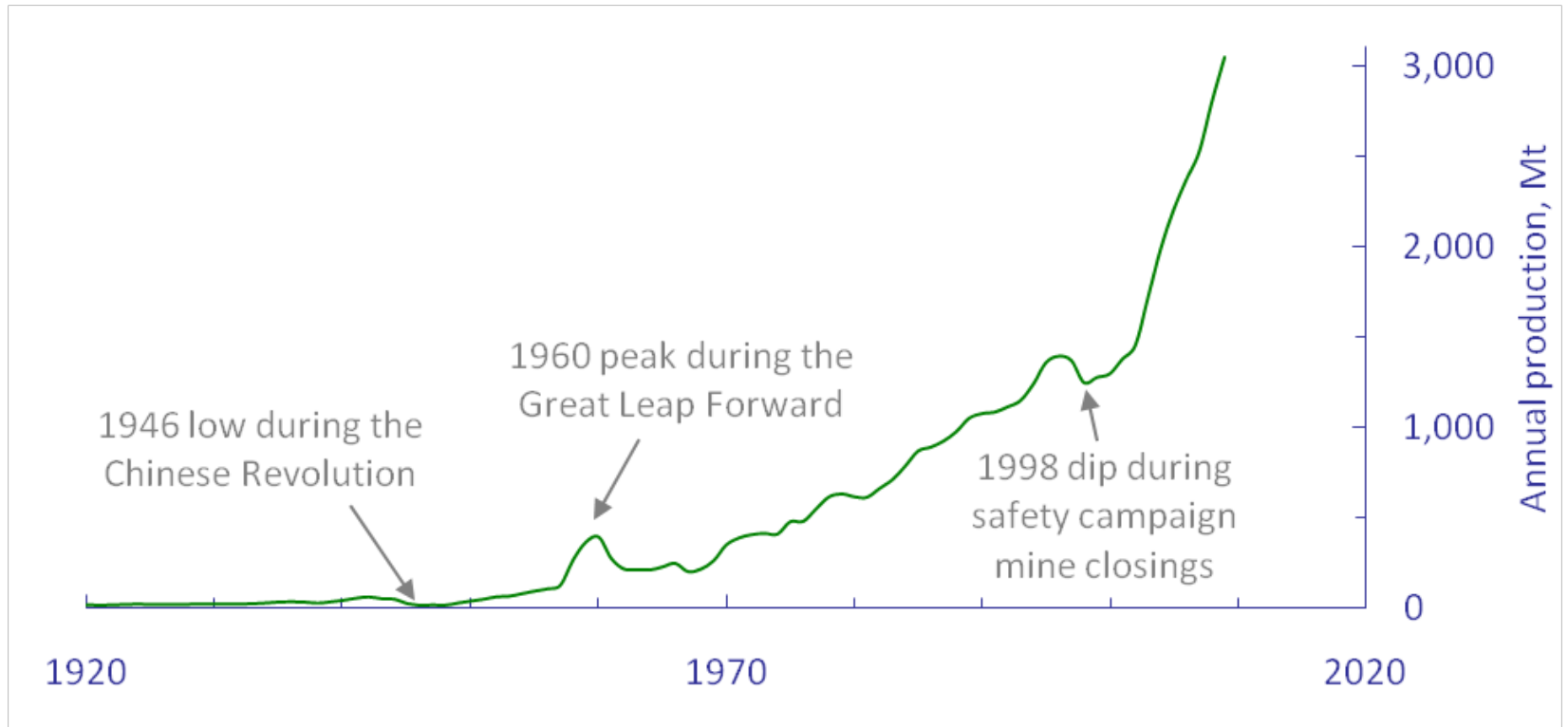
- SASOL = South African Synthetic Oil company
- Coal production increased dramatically during the boycott period

Probit Transform for Africa



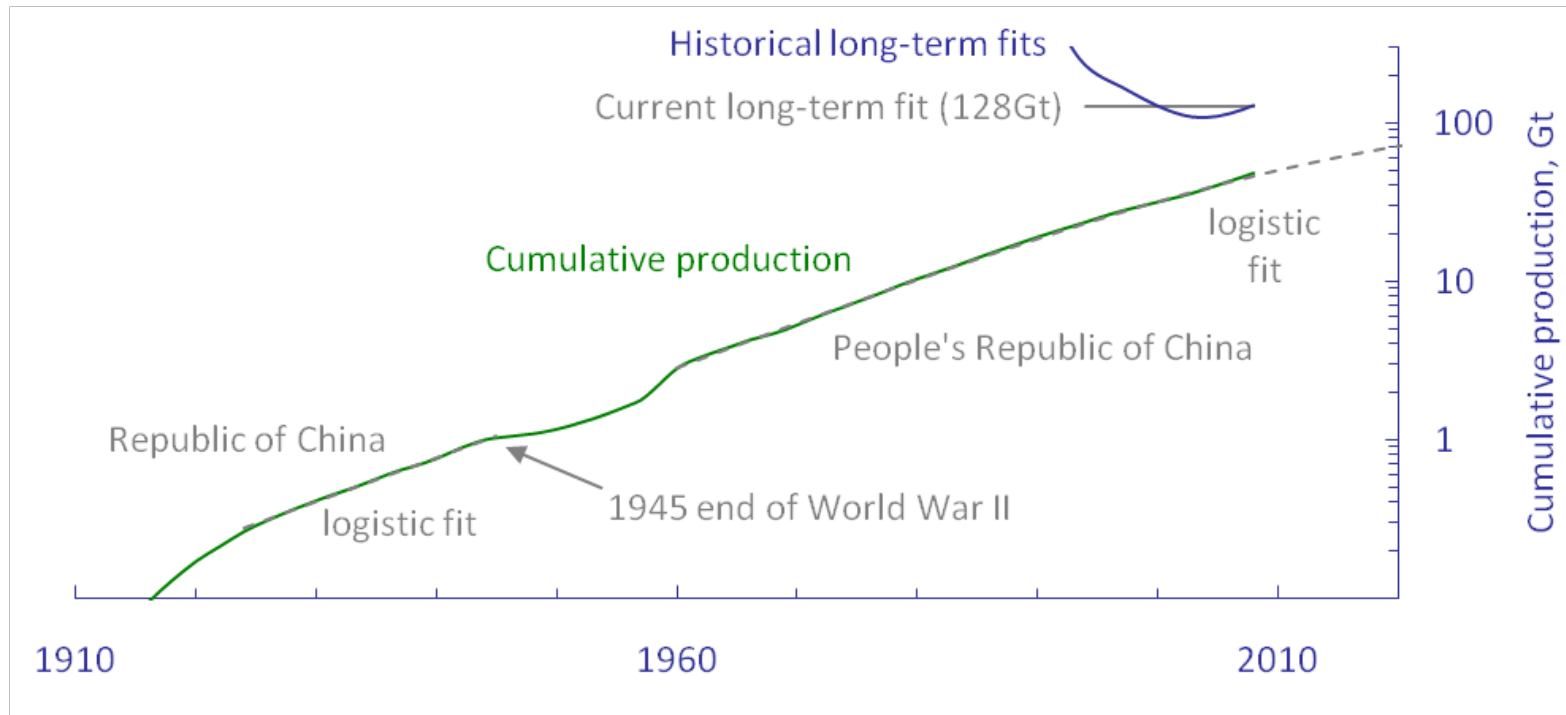
- Projection for the ultimate is 18Gt (32% of reserves + cumulative)

Chinese Coal



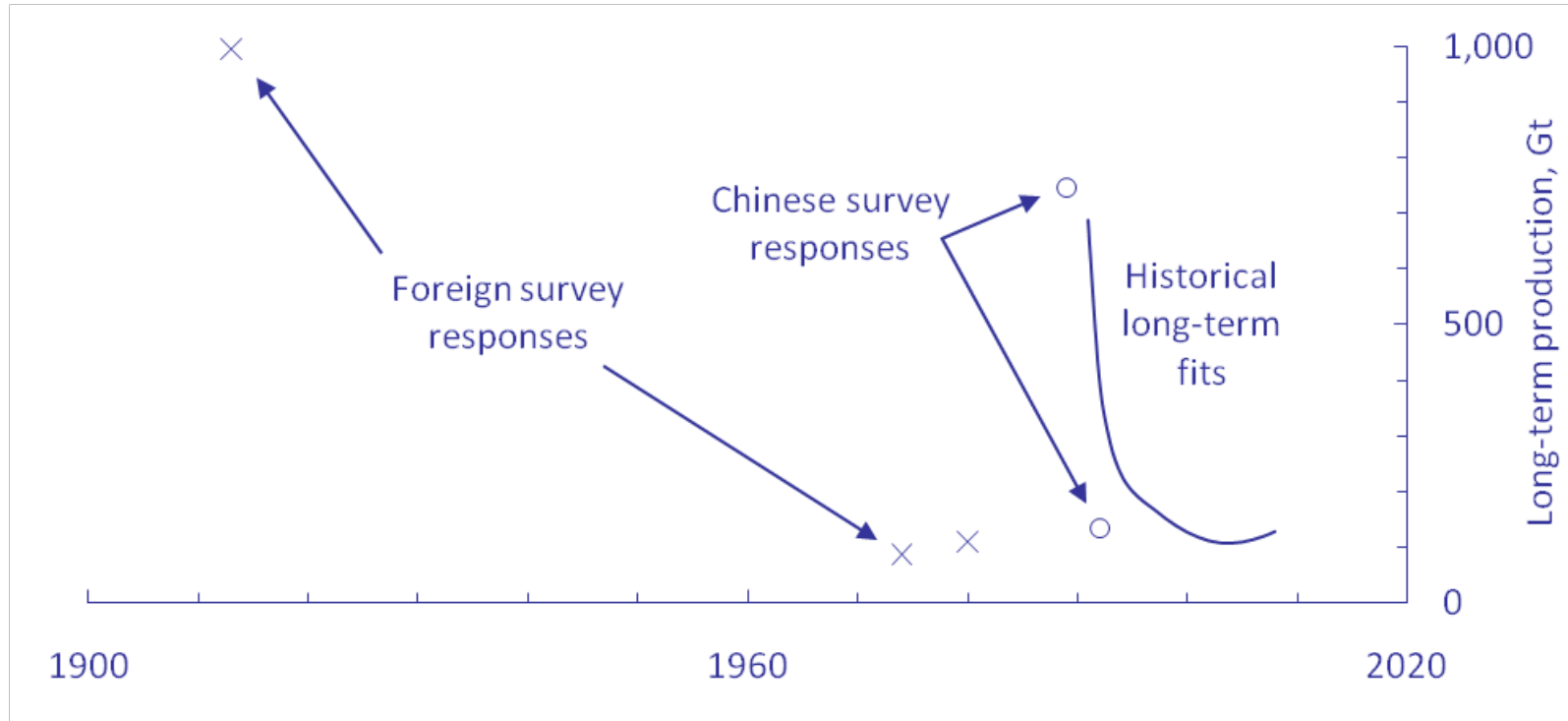
- 44% of world's production in 2009
- Serious problems with the reliability of the production data

Cumulative Production versus Historical Fits



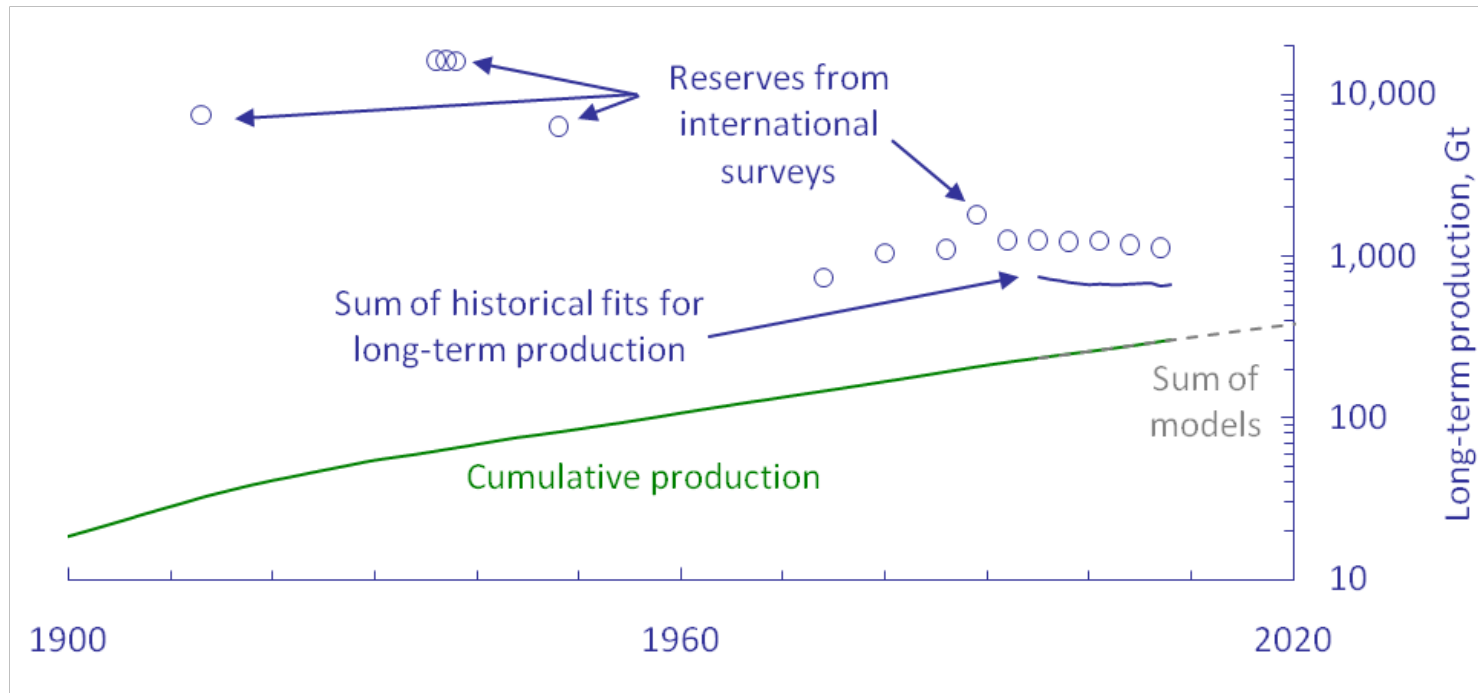
- For the current fit, r^2 is 0.99951
- Long-term production fit is 139Gt (90% of reserves + cumulative)

Long-term Fits Compared with Reserves



- Reserves submitted to World Energy Council in 1989 and 1992 differ by 6:1

World Coal Production



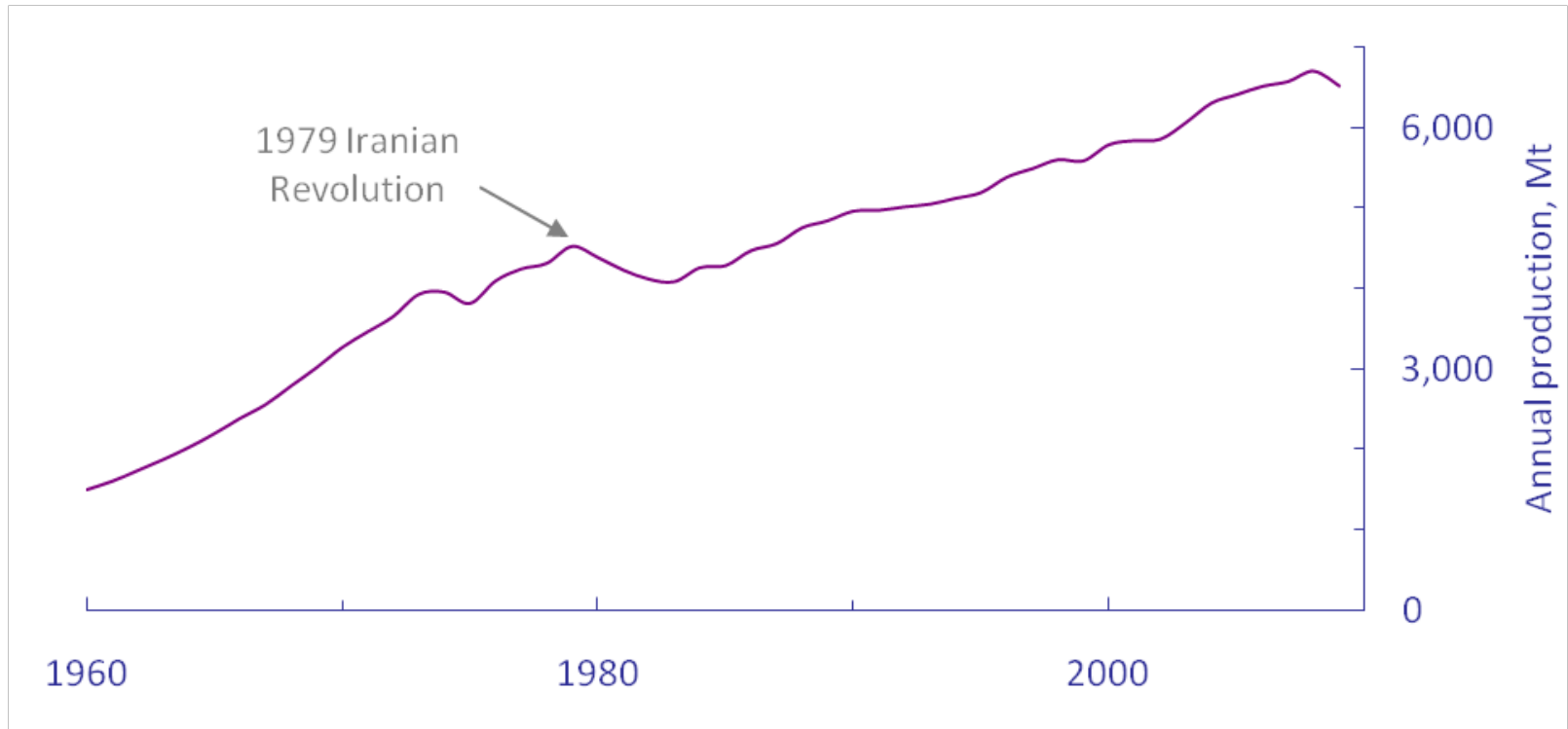
- Other regions not shown, but are available on line
- 14% range from 1995 on
- **Current long-term fit is 680Gt, 60% of reserves + cumulative**
- IPCC range for production through 2100 is 355 to 3,500Gt

Where Does the IPCC Get Its Coal Numbers?

World Energy Council survey	Proved recoverable reserves, Gt	Additional recoverable reserves, Gt
1992	1,039	702
1995	1,032	680
1998	984	3,368
2001	984	409
2004	909	449
2007	847	180

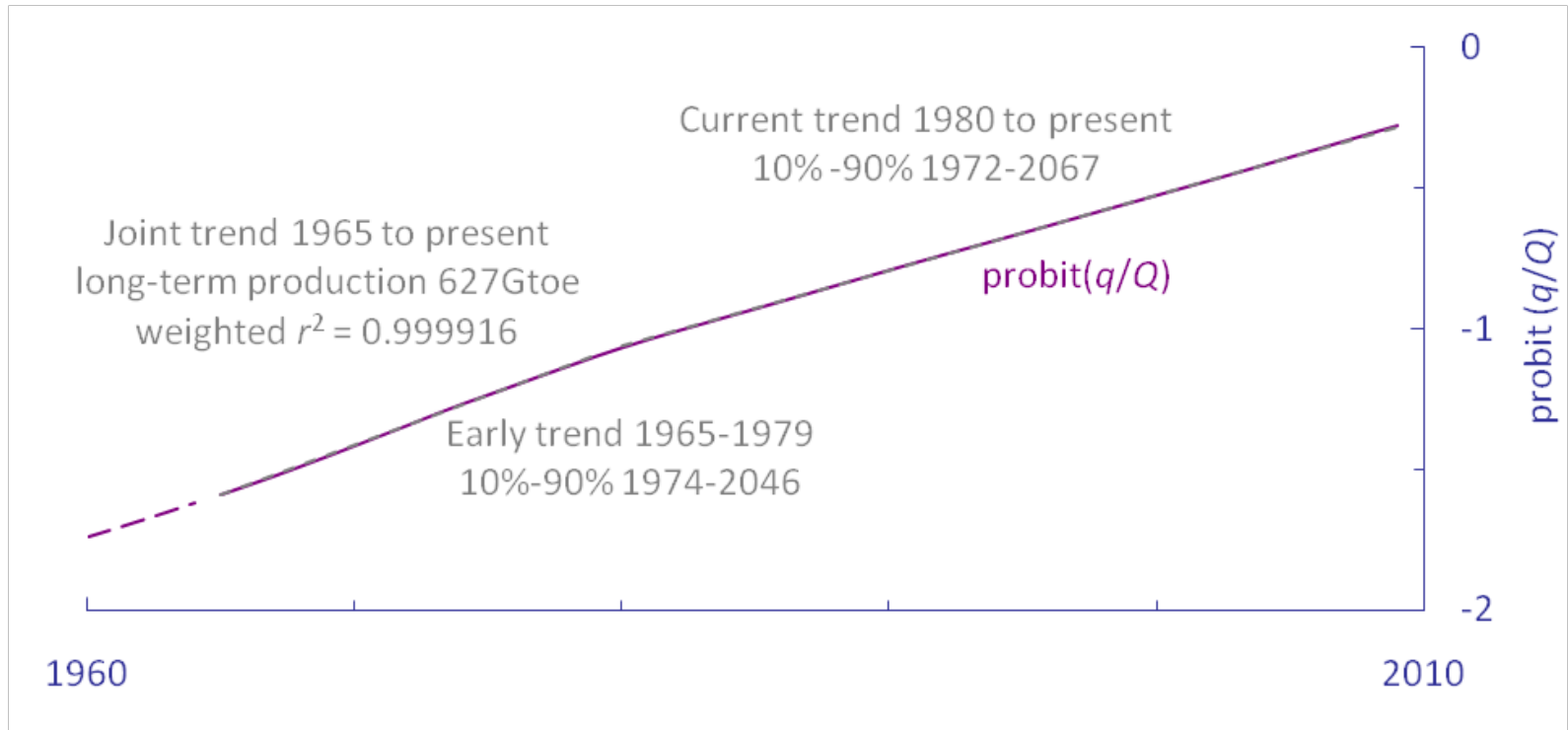
- The scenario report SRES (2000) references the 1995 and 1998 surveys
- The IPCC chose to use additional recoverable reserves and they also chose 1998 (3,368Gt) instead of 1995 (680Gt)
- Additional recoverable reserves are now 19 times smaller than in 1998
- The 4th Assessment report notes the 2004 survey results, and includes 100,000EJ (5,000Gt) as a “possible resource” with no reference

World Oil and Gas Production



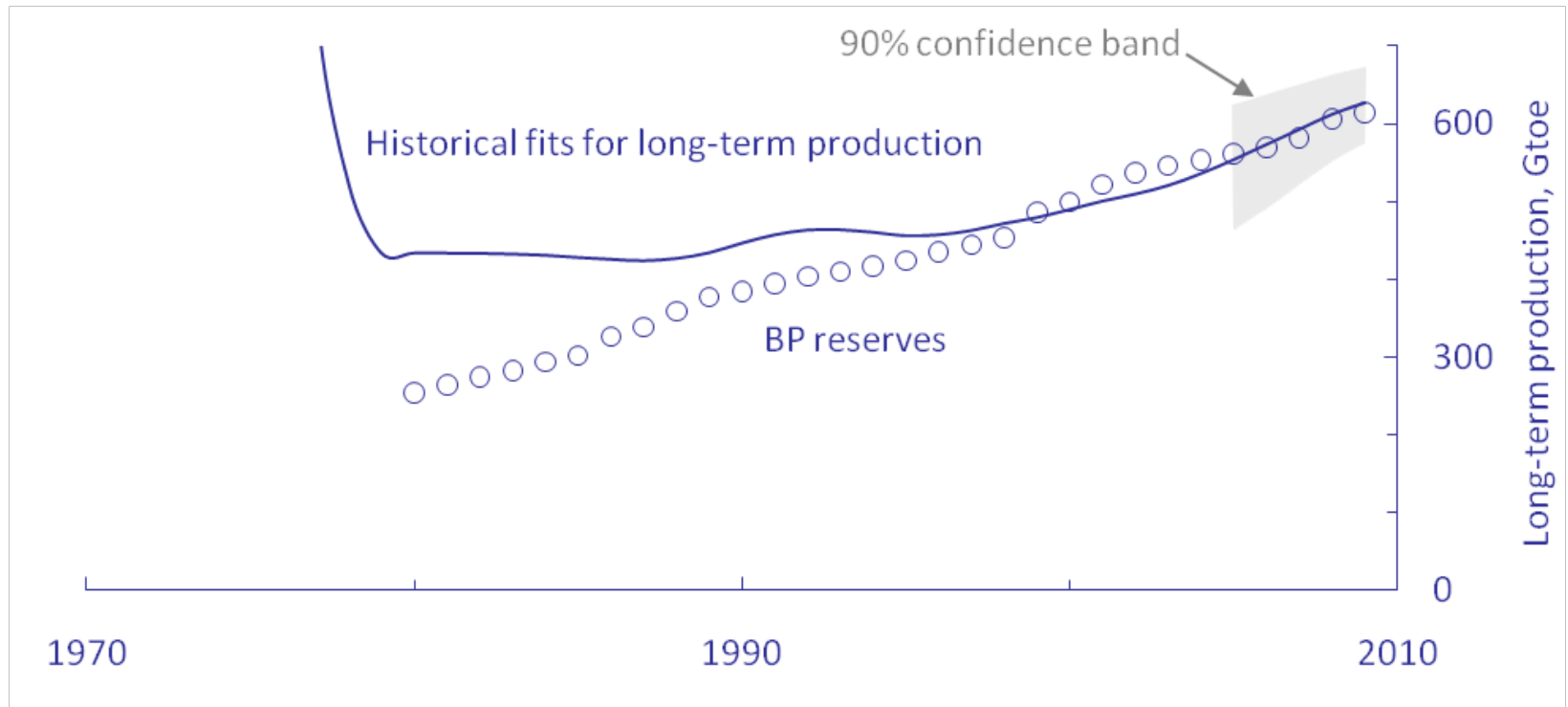
- 7.33 barrels of oil = 1 metric ton, toe = metric tons of oil equivalent
- Natural gas added as the energy equivalent

Probit Transform for World Oil and Gas



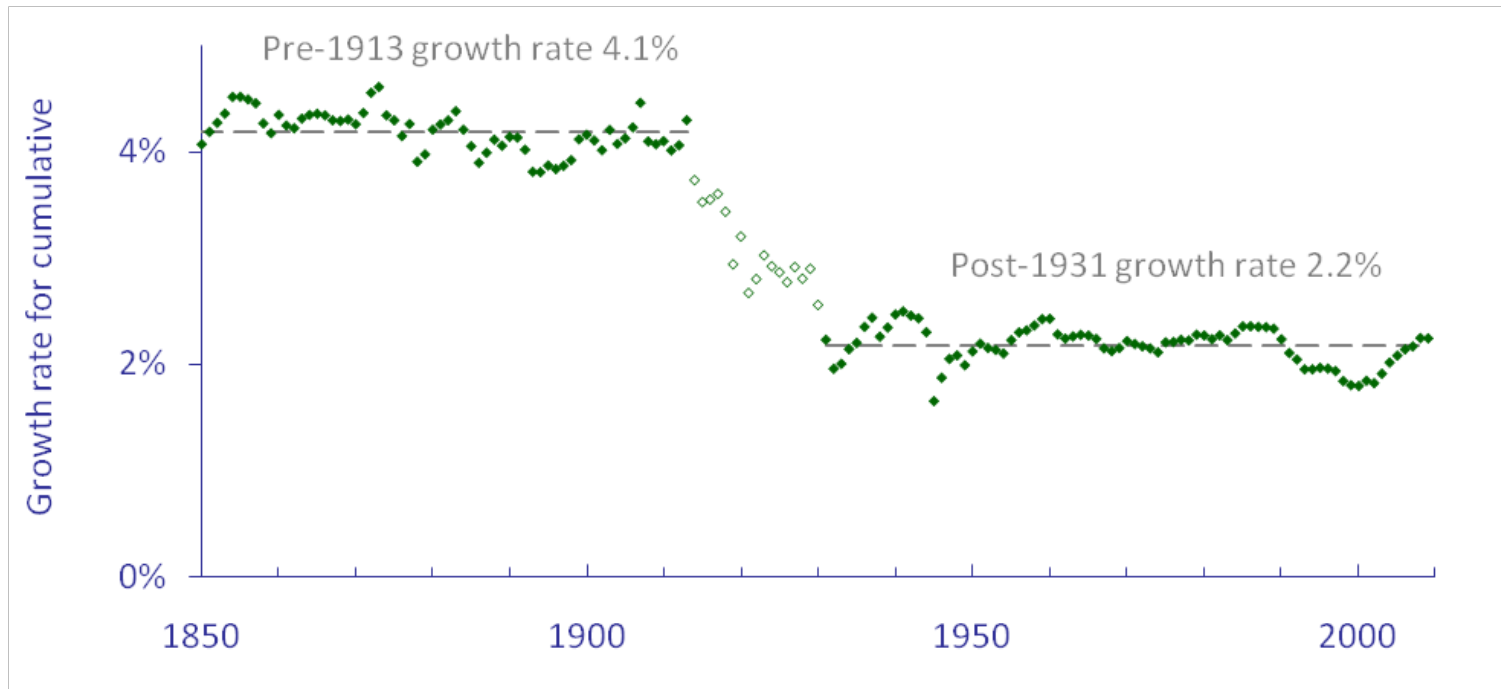
- Change in slope, like African coal, but in the other direction

Historical Long-term Fits for World Oil and Gas



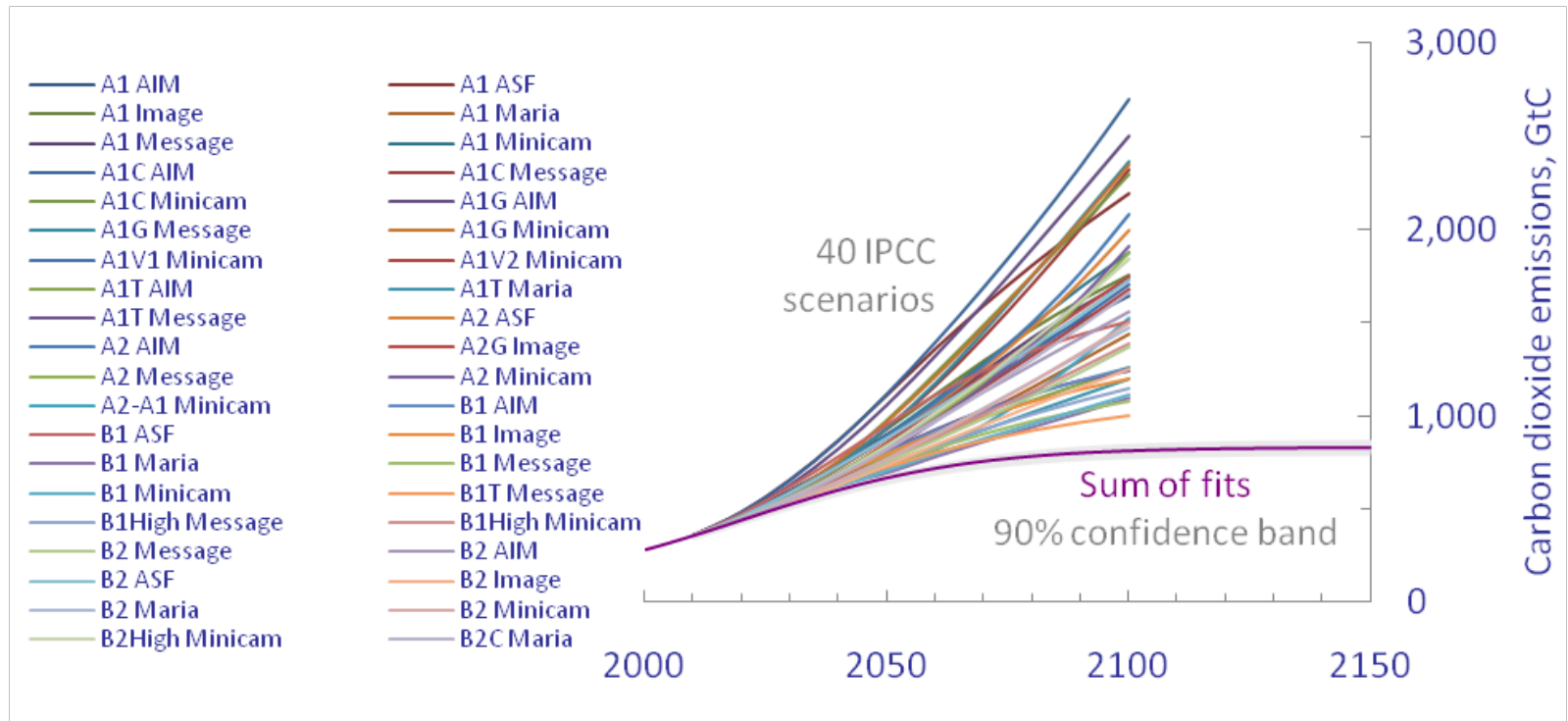
- Residuals decorrelated by AR2 process — passes Ljung-Box-Pierce test
- 90% confidence band from 1,000 bootstrap replications
- Current confidence interval is 576 to 671Gtoe
- Close to BP's reserves + cumulative production, 596Gtoe

Why Not Do a Curve Fit for World Coal Production?



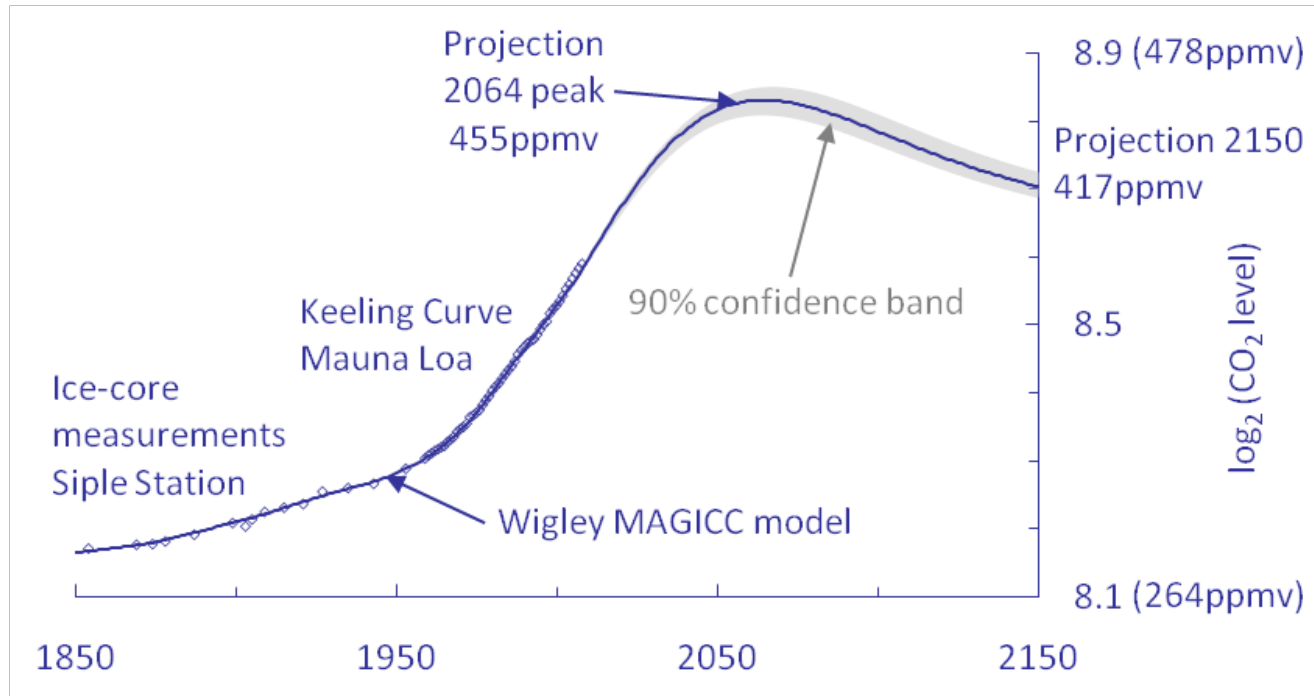
- 96% of production through 1913 was Europe and the United States
- Exponential growth since 1931 (not logistic or normal)
- Coal markets are regional — only 15% of the world's coal is exported

Carbon-Dioxide Emissions

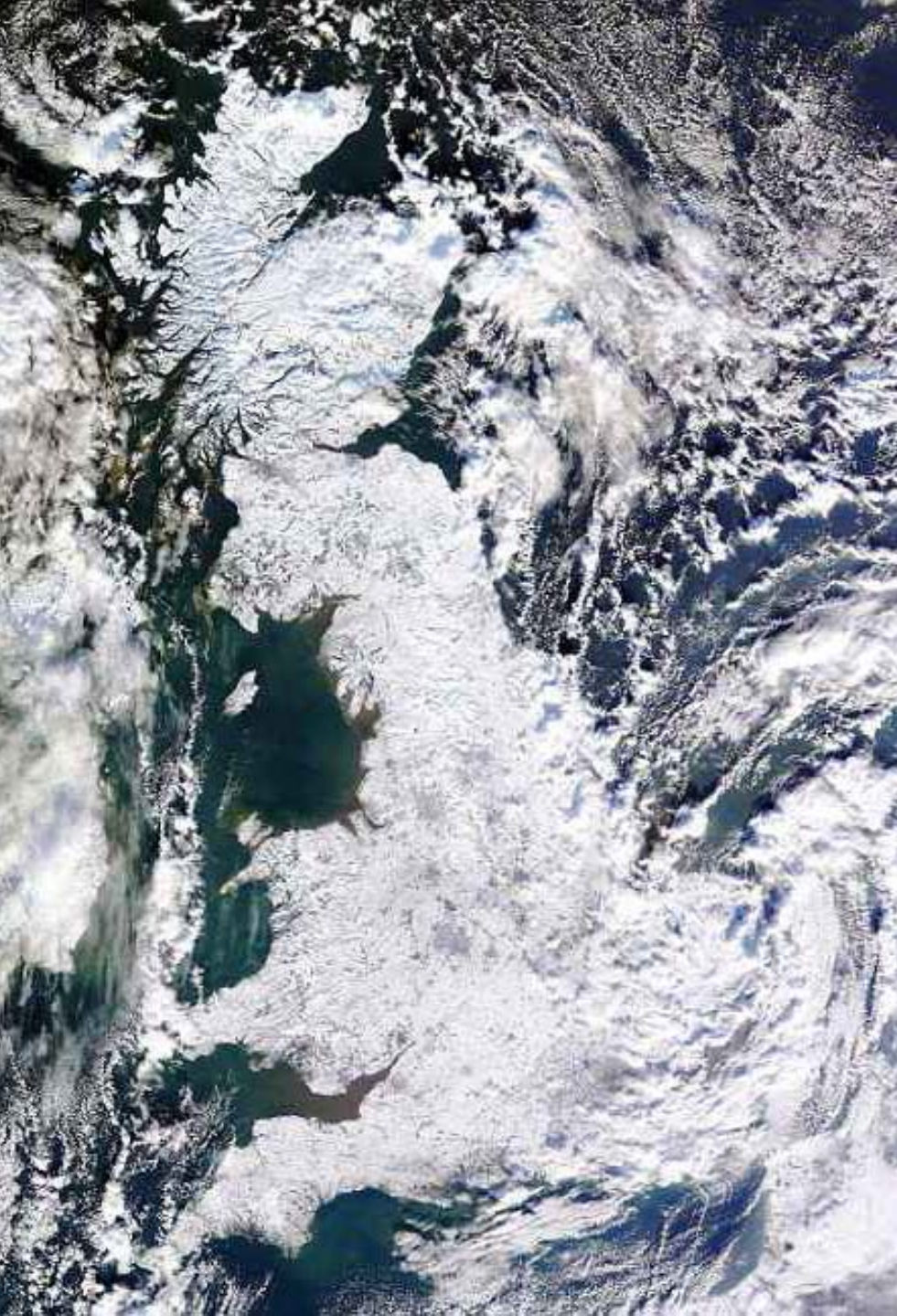


- Carbon coefficients for oil, gas, and coal from the IPCC 4th Assessment
- Projection is less than any of the IPCC scenarios

CO₂ Levels from Tom Wigley's MAGICC



- Peak in 2064 is close to year of projected 90% exhaustion for fossil fuels in 2068
- Fraction of variance accounted for (R^2) is 99.93% (model has many parameters)
- 64% of the way to the top from the 1850-1900 average — only the remaining 36% is accessible to policy
- Maximum width of confidence band corresponds to 0.1°C at the IPCC recommended sensitivity of 3°C for a doubling of CO₂



Climate
Research
Unit (CRU)
emails

Phil Jones — Director of the Climate Research Unit (CRU)



- Leader of effort to develop the most important world land temperature series (CRUTEM3) — the only world land thermometer series that goes back to 1850
- The British MET office has announced a three-year review of the temperature record

The Temperature Record

Phil Jones to Michael Mann (March, 2004)

“Recently rejected two papers (one for JGR and for GRL) from people saying CRU has it wrong over Siberia. Went to town in both reviews, hopefully successfully.”

Tom Wigley to Phil Jones (November, 2009)

“Land warming since 1980 has been twice the ocean warming -- and skeptics might claim that this proves that urban warming is real and important.”

Tom Wigley to Phil Jones (November, 2009)

“Here are some speculations on correcting SSTs [sea surface temperatures] to partly explain the 1940s warming blip. If you look at the attached plot you will see that the land also shows the 1940s blip (as I'm sure you know). So, if we could reduce the ocean blip by, say, 0.15 degC, then this would be significant for the global mean – but we'd still have to explain the land blip.”

The GHCN Station in My Father's Home Town

- Detroit Lakes, Minnesota, population 8,000 (rural for GHCN)
- GHCN 42572753004 1896-2006
- Average high in July 27°C — trend 0.0°C per century
- Average low in January -21°C — trend +4.1°C per century
- Attached to the KDLM radio station on the edge of a marsh
- Air conditioner moved from the roof to the ground in May 1999 — 4.1°C rise for July 1999 high (0.5°C average rise for ten closest stations)
- Propane tank for heating the station (on air at 5:30am)



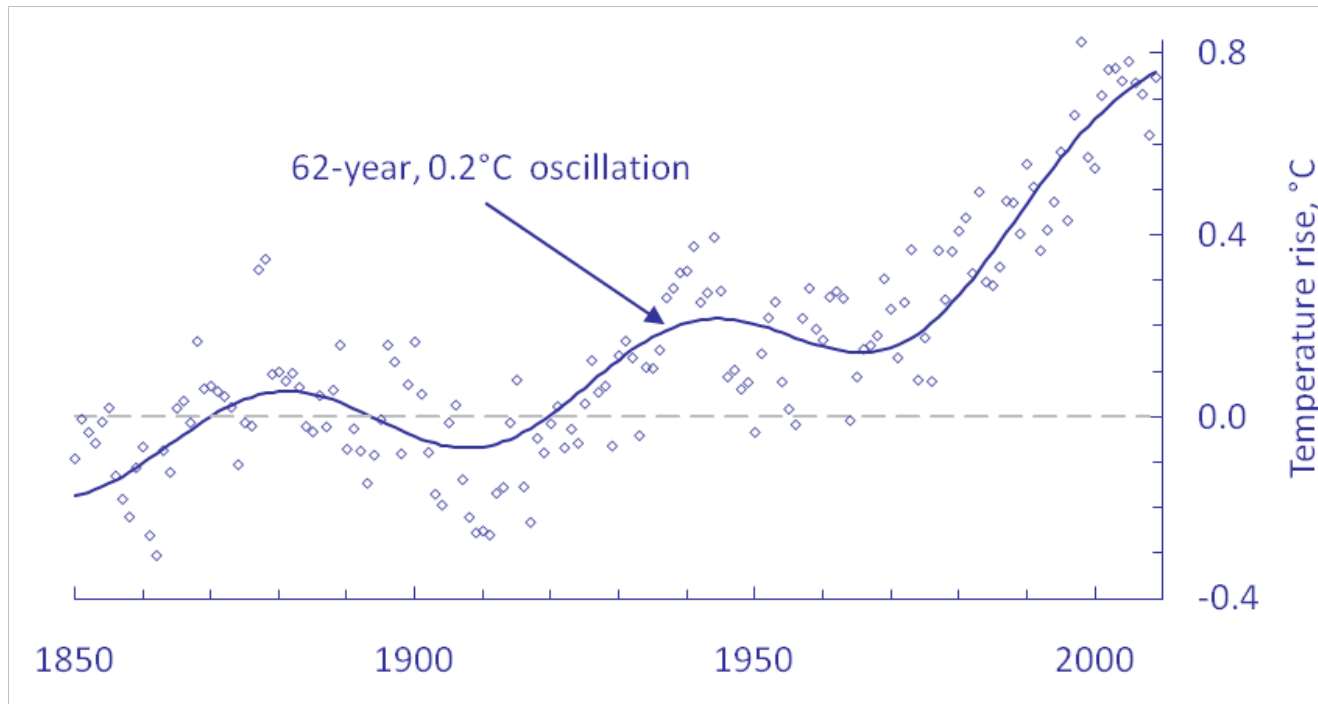
Photo 2007 by Don Kustuch

2009 update — sensor moved into marsh

Temperature Data Problems

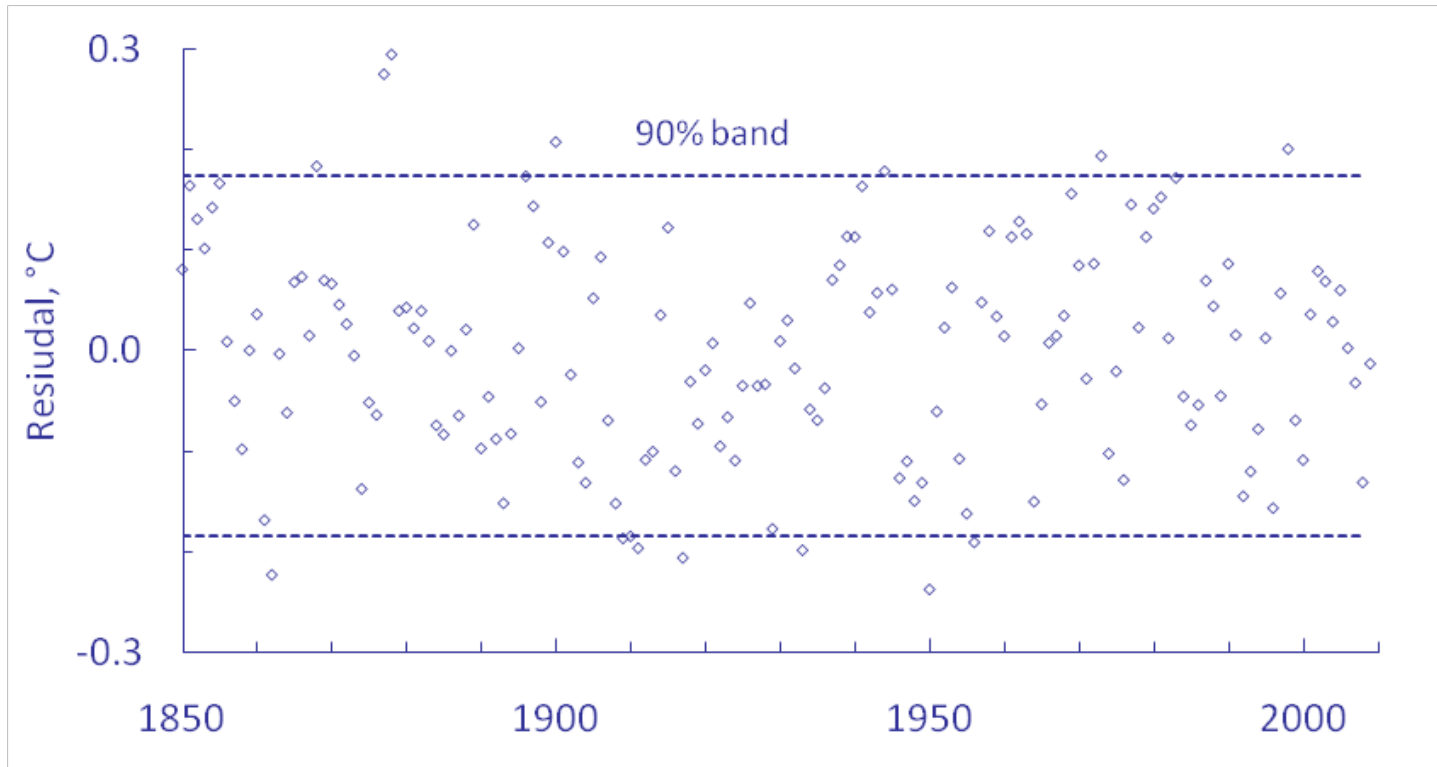
- The quality of temperature data is poor — I believe there is likely to be a significant uncorrected error in the temperature trend
- I will try to compensate for this by expressing the results as ratios — how close we are to the peak, compared where we were over the 1850 to 1900 period?

Correlation Model for Temperature



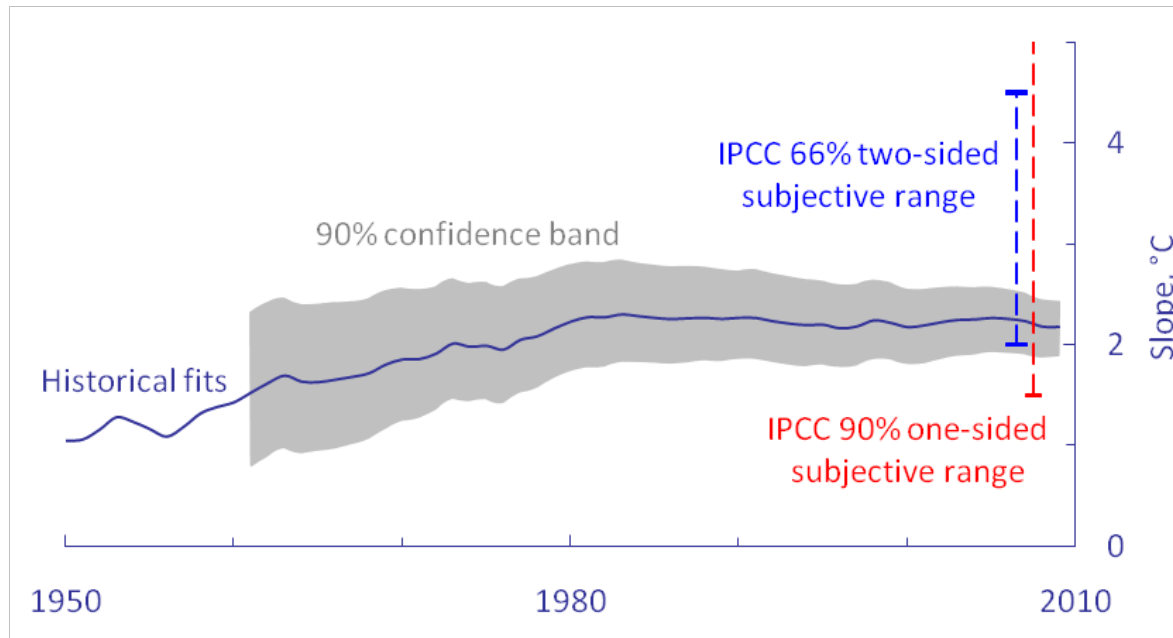
- Temperatures from the UK Hadley Centre and the Climate Research Unit
- Modified version of the model Michael Schlesinger and Navin Ramankutty used to identify the Atlantic Multidecadal Oscillation
- Dynamics following the two-time constant response of Isaac Held *et al.*
- Model is $T = T_0 + T_1 \log_2(\text{CO}_2)_d + \text{oscillation}$

Temperature Residuals



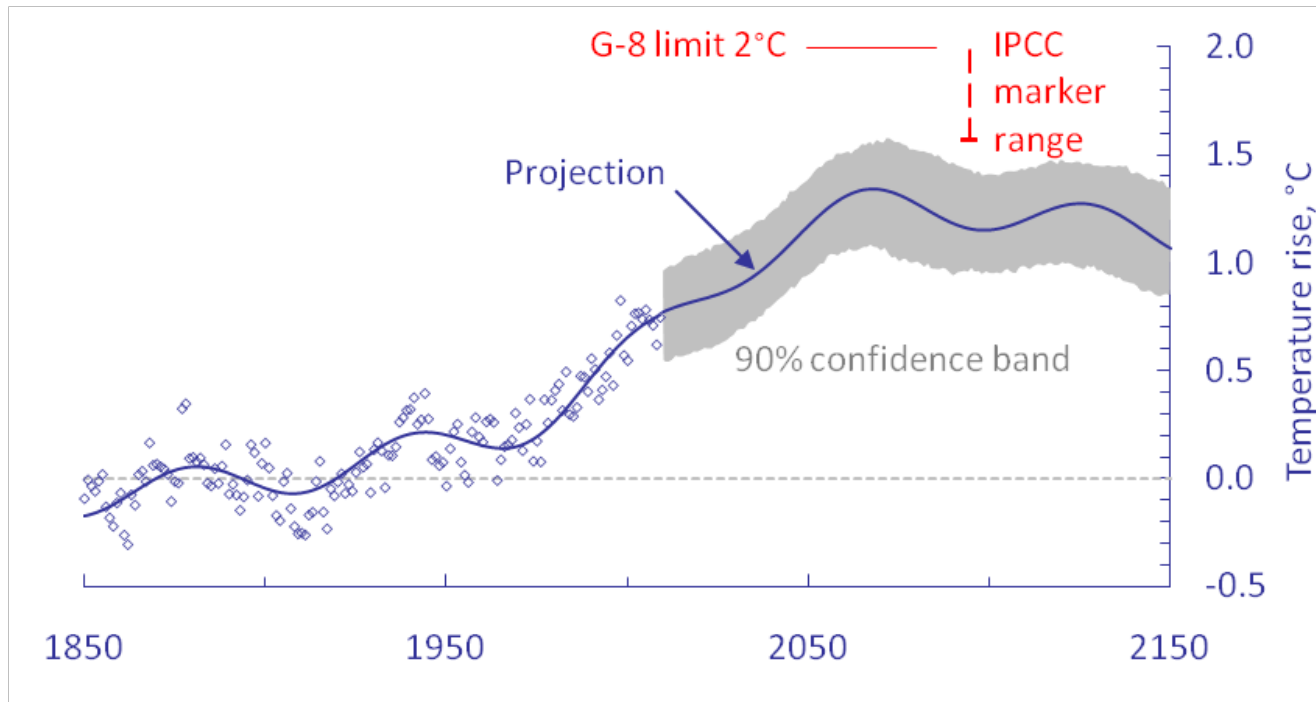
- Fraction of variance accounted for (R^2) is 81%
- Residuals can be decorrelated by AR1 process ($r = 0.45$) — passes Ljung-Box-Pierce chi-square test ($p = 0.55$, where $p < 0.05$ indicates significant correlation)
- Large fluctuations are a problem for policy

Confidence Band for Association between Temperature and $\log_2(\text{CO}_2)$



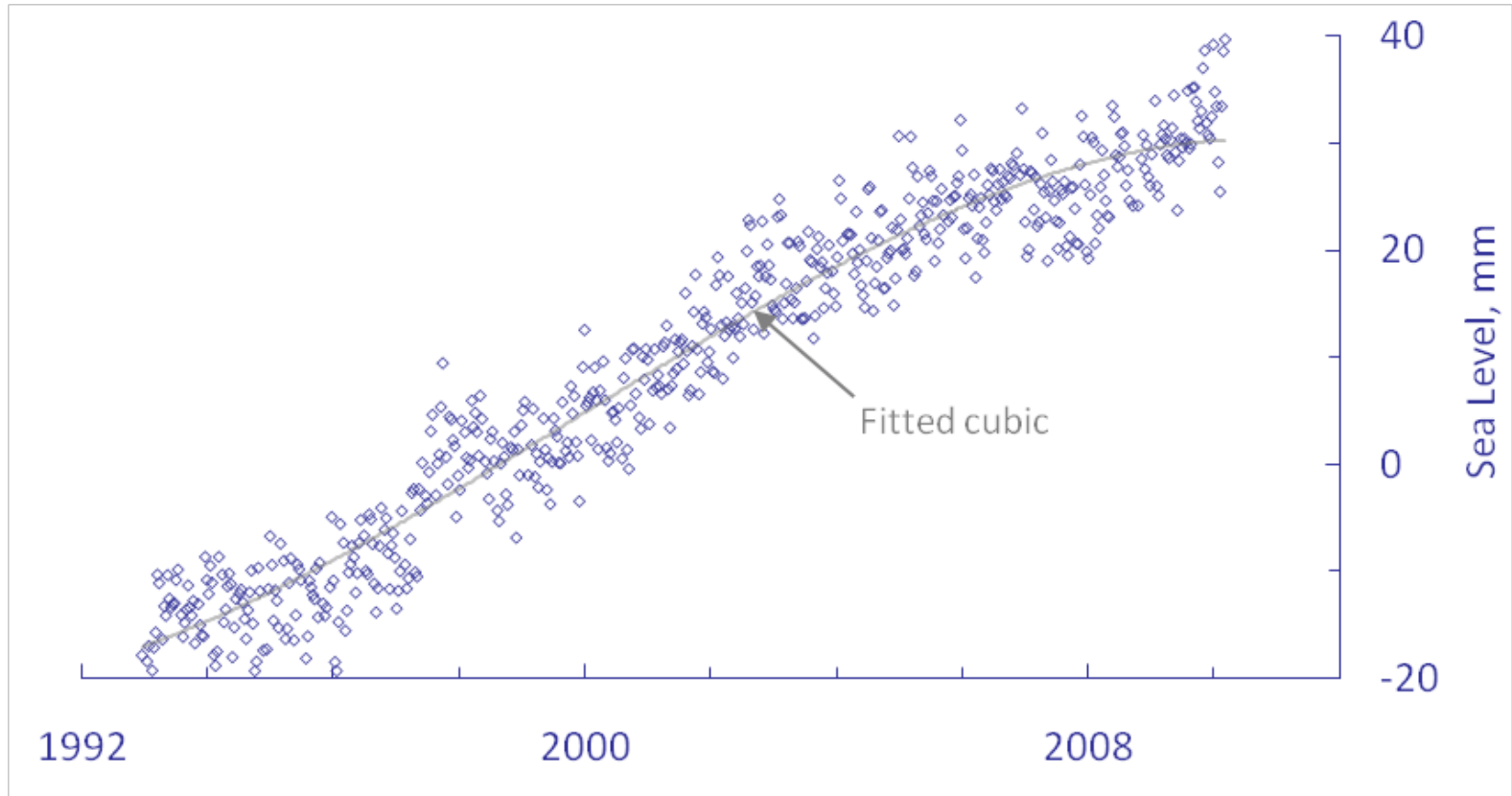
- 90% confidence band from 1,000 bootstrap replications — 1.9°C to 2.4°C
- Confidence band is completely consistent with IPCC's range for temperature sensitivity, but narrower — and stable for 50 years
- This slope is not exactly comparable to the IPCC sensitivity, where black carbon and sulfate aerosols and greenhouse gases like methane and nitrous oxide are considered separately

Temperature Projection



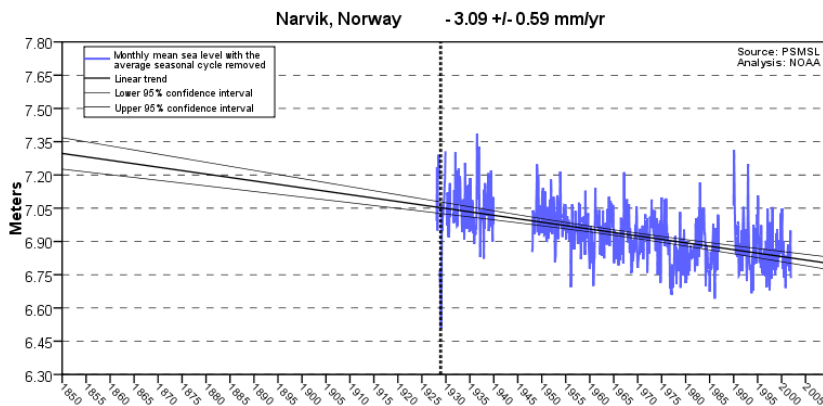
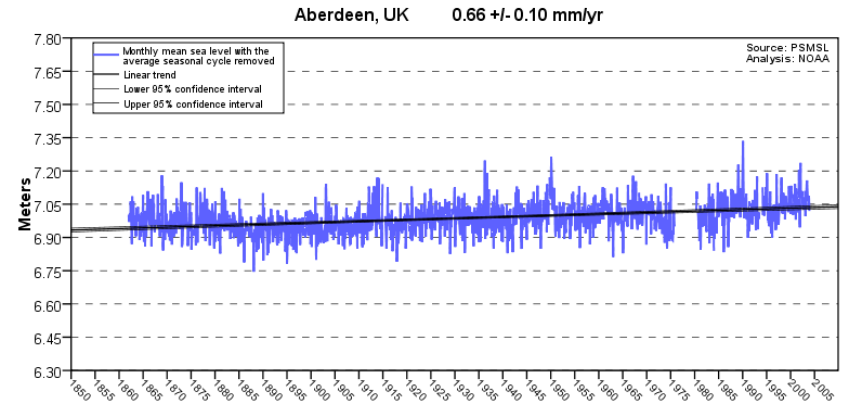
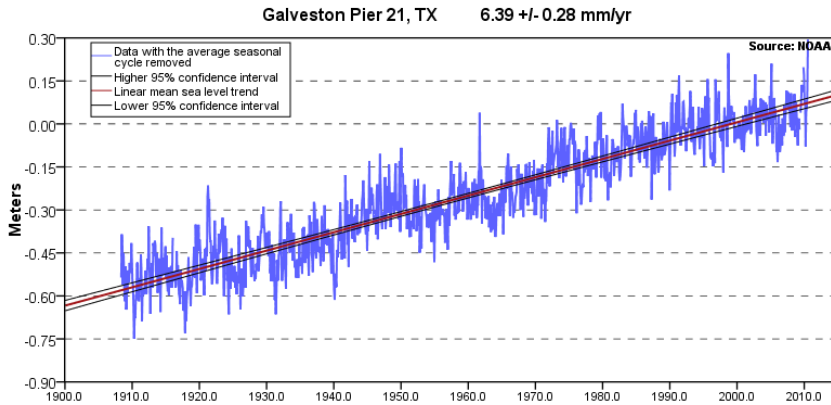
- Confidence band from 1,000 bootstrap replications — includes both short-term fluctuations and model uncertainty
- Projection and confidence band are below the IPCC range, because of smaller fossil fuel production
- 56% of the way to the projection peak from the 1850-1900 average

Satellite Radar Sea-Level Measurements



- TOPEX and JASON satellites — data from the University of Colorado
- 29mm rise in the last ten years

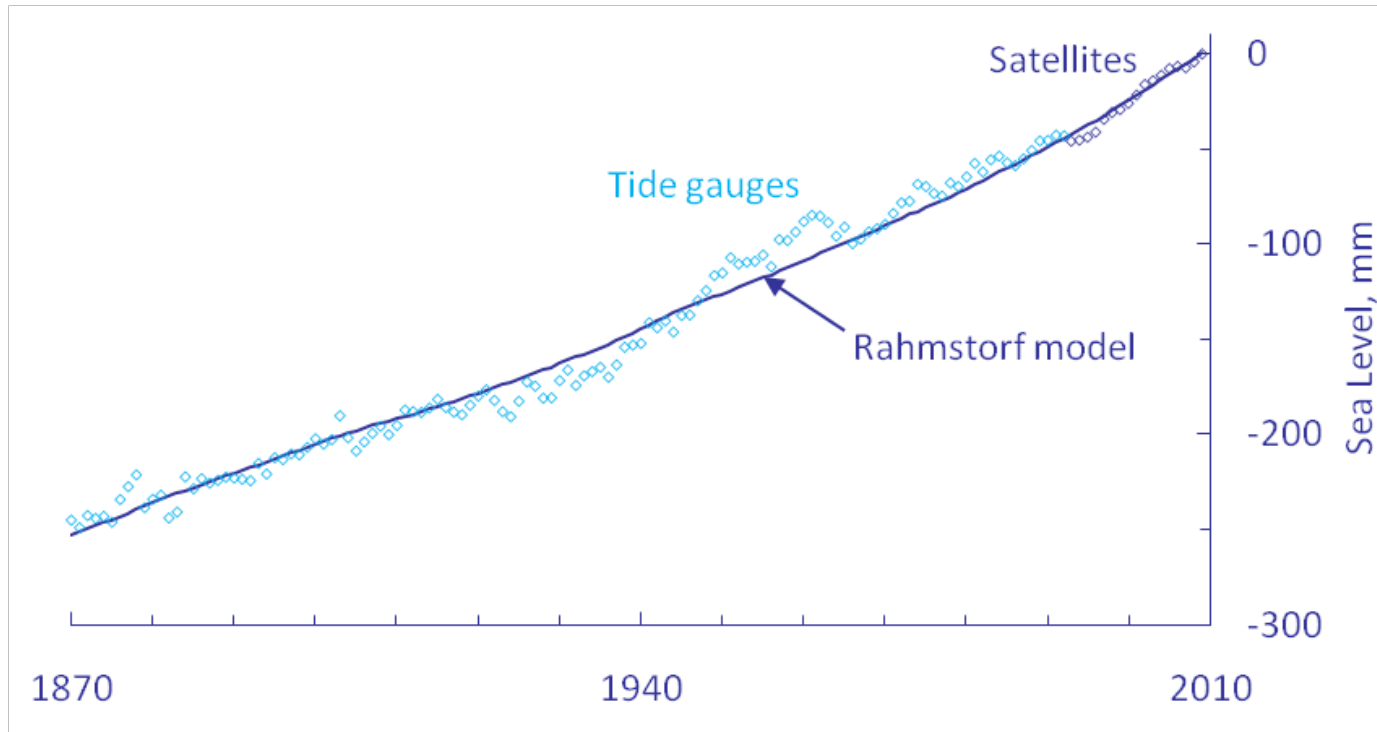
Sea Level Trends vary Locally



- Aberdeen, Scotland: + 7mm/decade
- Galveston, Texas: + 64mm/decade
- Narvik, Norway: – 31mm/decade
- Ground water: + 8mm/decade
- Reservoirs: – 2mm/decade

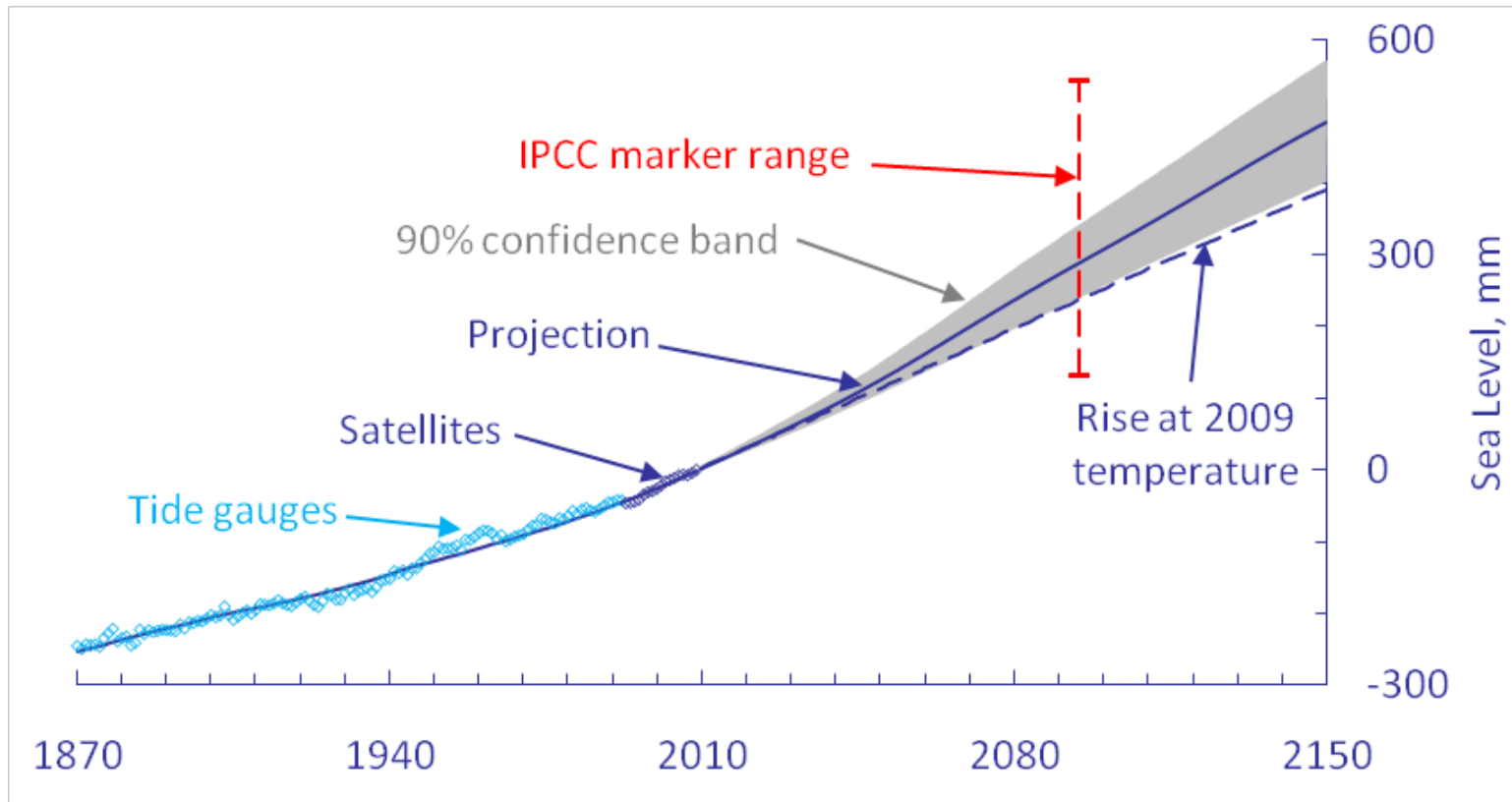
As with temperature, we need to be aware of the possibility of an uncorrected error in the trend — I will state results in the form of a change in the trend

Rahmstorf Model for Sea Level



- Tide gauge data from John Church and Neil White
- Model for rise rate is $R = R_0 + R_1 T$ mm per year — model is more speculative than for temperature
- Fraction of variance accounted for (R^2) is 98.8%
- Residuals decorrelated by AR1 process ($r = 0.78$) — passes Ljung-Box-Pierce test ($p = 0.34$)

Sea-Level Projection



- 90% confidence band from 1,000 bootstrap replications — completely consistent with the IPCC range, but narrower
- Portion of sea level rise through 2150 that is associated with future temperature rise is 93mm — this is the part accessible to policy

Long Beach Subsidence — 9m!

- Picture taken by Roger Coar in 1959 — his dog's name was King
- With the permission of the Long Beach Historical Society



Summary

- Oil, gas, and coal
 - The projection for long-term world oil and gas production is consistent with the BP reserves
 - Long-term production estimates for coal from geological reserves are available early, but they are too high (6× for the UK, 2× for Pennsylvania anthracite)
 - Projection for long-term world coal production is 60% of the reserves plus cumulative production — projection range has been within a 14% band since 1995
- Climate
 - 64% of the change in CO₂ forcing appears to have already occurred
 - 56% of the projected temperature rise appears to have already occurred
 - Portion of sea level rise through 2150 that is associated with future temperature rise is 93mm

This work has been supported entirely by Caltech discretionary funds