

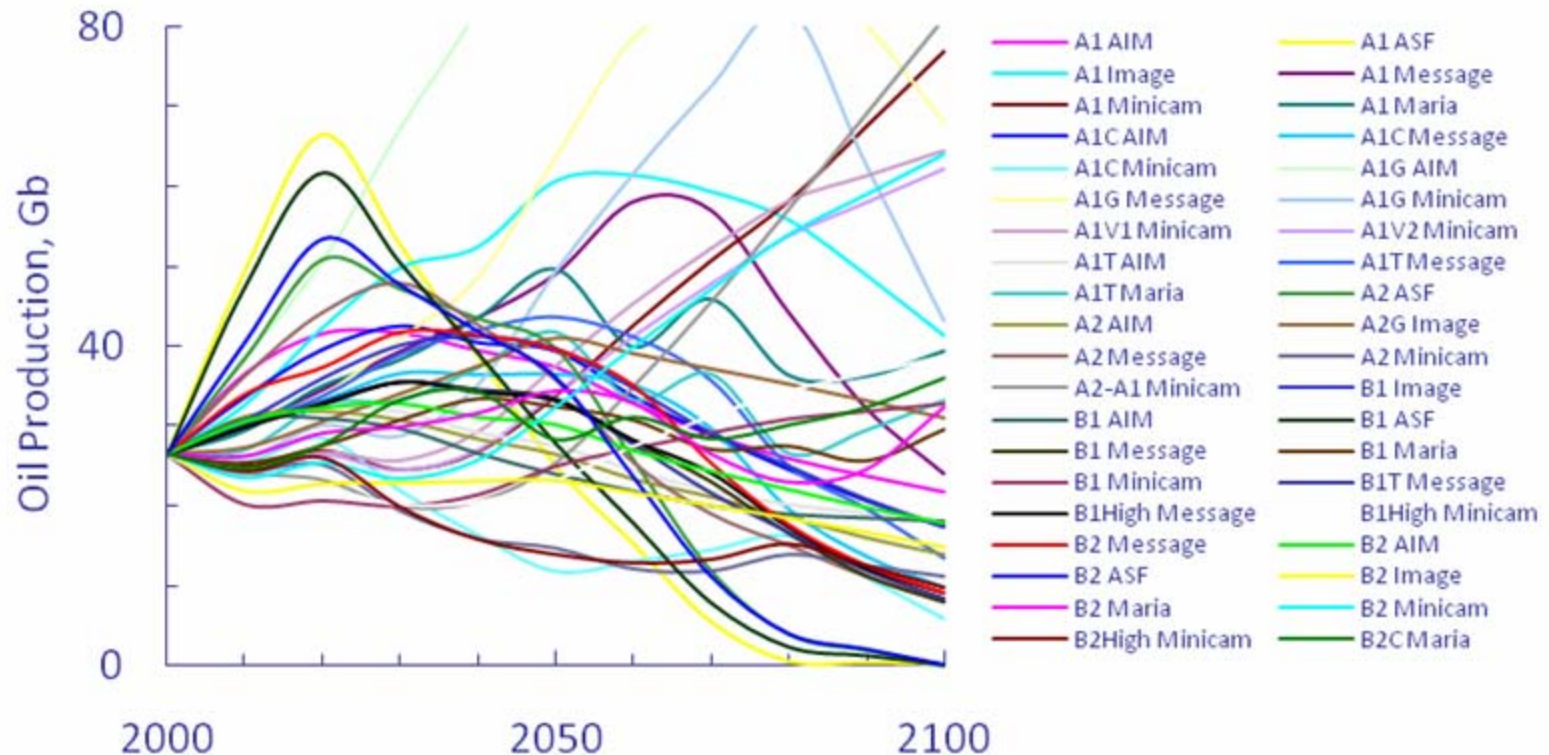
Coal as a Resource and Climate Change

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The UN Panel on Climate Change (IPCC)

- Released 4th Assessment Report in 2007
- For climate projections, the IPCC uses 19 physics-based computer models — range for temperature sensitivity in the models is 2.1 to 4.4°C/2xCO₂
- For fossil-fuel 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 2100)

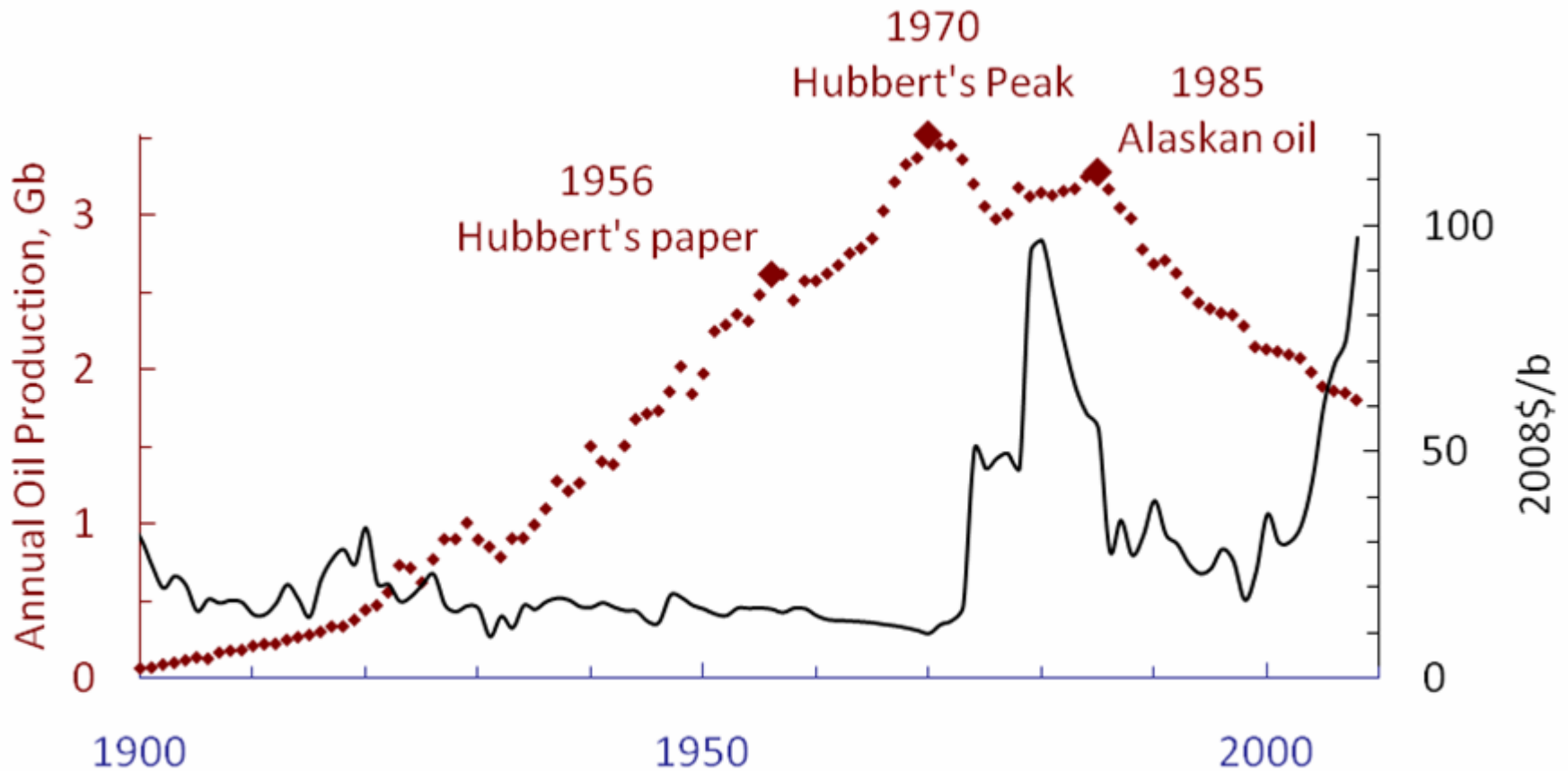
Goal is to Assess Accuracy and to Reduce the Uncertainties

- Oil, gas, and coal: curve fits to the production histories
 - US oil — Hubbert's peak
 - British coal — The Coal Question
 - World oil, gas, and coal
- Climate: curve fits to the historical data
 - Temperature
 - Sea level

Advantages of Curve-Fitting Approach

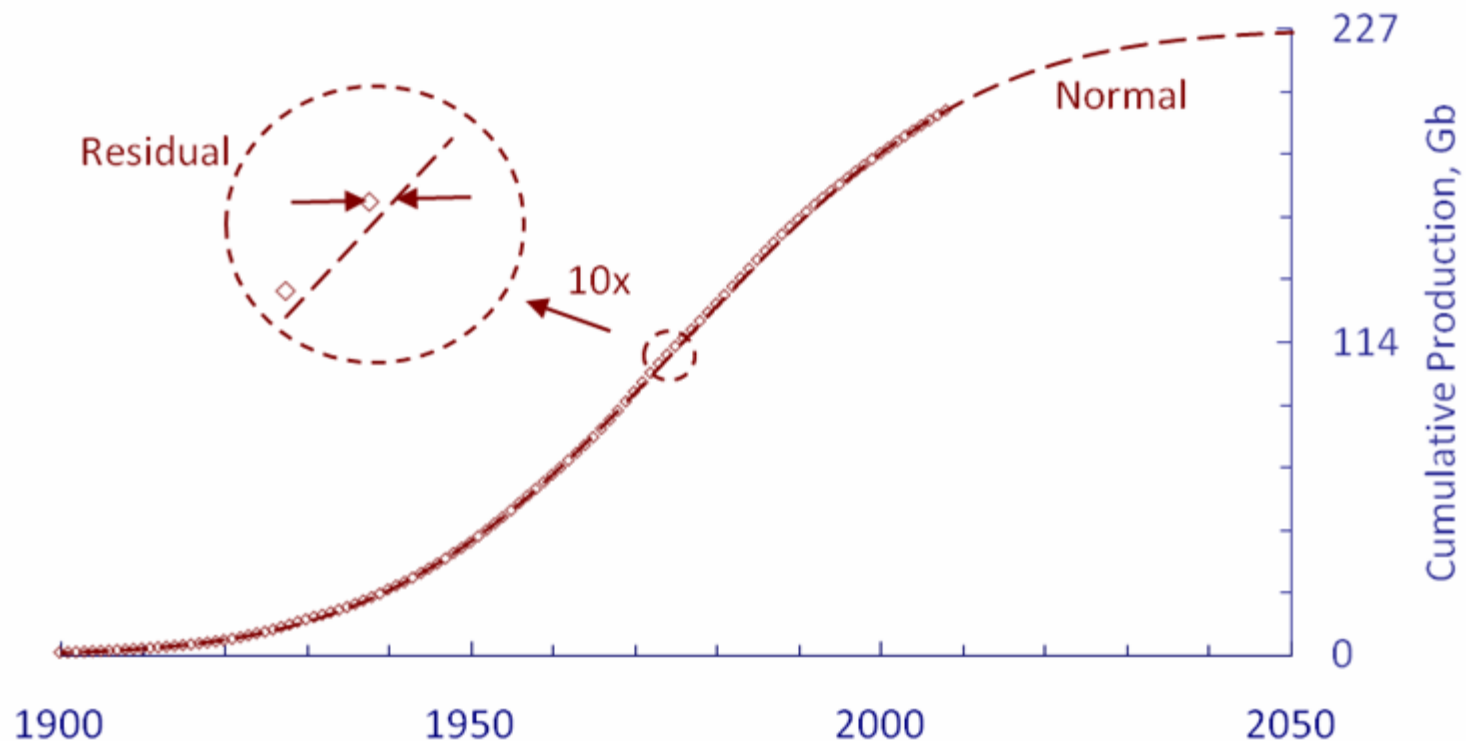
- Accuracy assessment (mature coal regions, stability of historical projections)
- Standard statistical calculations of uncertainty (confidence interval based on decorrelating residuals and replications)
- Curve fits for oil, gas, and coal give a separate geological factor (ultimate production) and economic factor (time for exhaustion)
- Curve fits for temperature and sea level allow a comparison between humanity's contribution and nature's
- Details of calculations are in the Excel workbook at rutledge.caltech.edu

US Crude-Oil Production



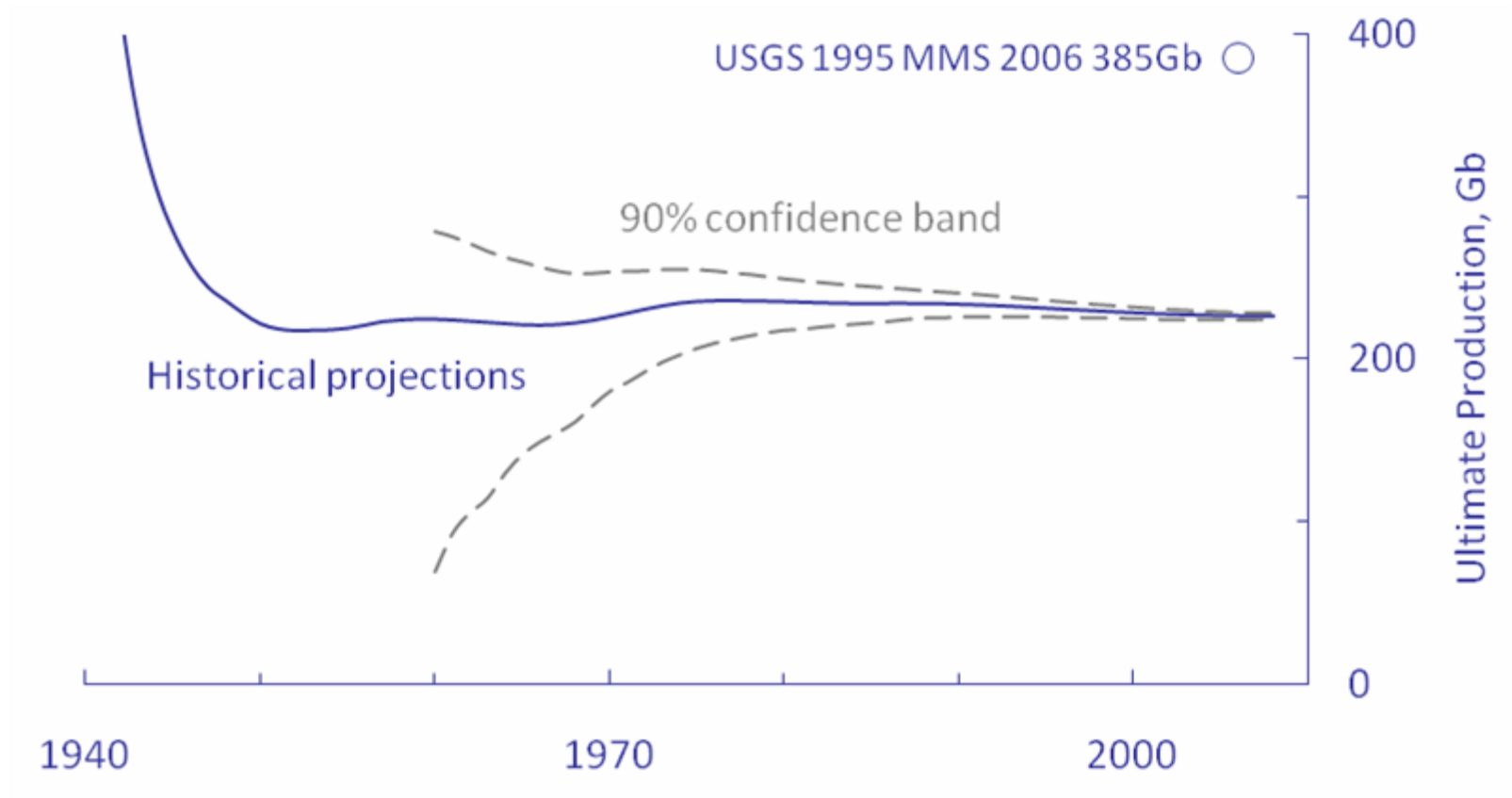
- Average price after the peak is 2.6 times higher — \$44 vs \$17
- Reserves have been equal to the following 10 years of production for many years

Cumulative Plot for US Crude Oil



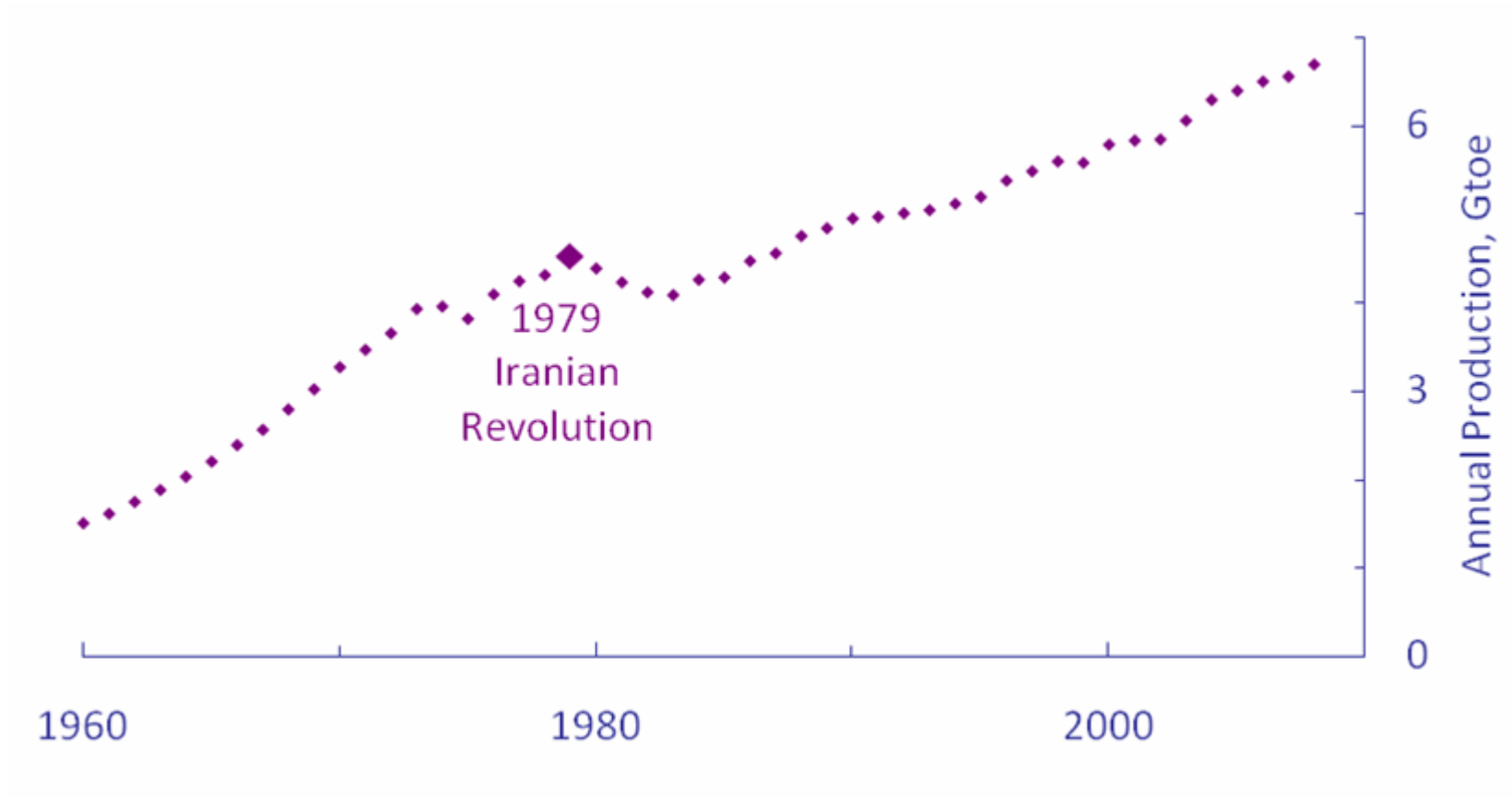
- Can use the production scale to give a projection for ultimate, 227Gb
- The fit minimizes the sum of the squares of the residuals, using Excel's Solver (2 seconds on a laptop)

Confidence Band for Historical Ultimates



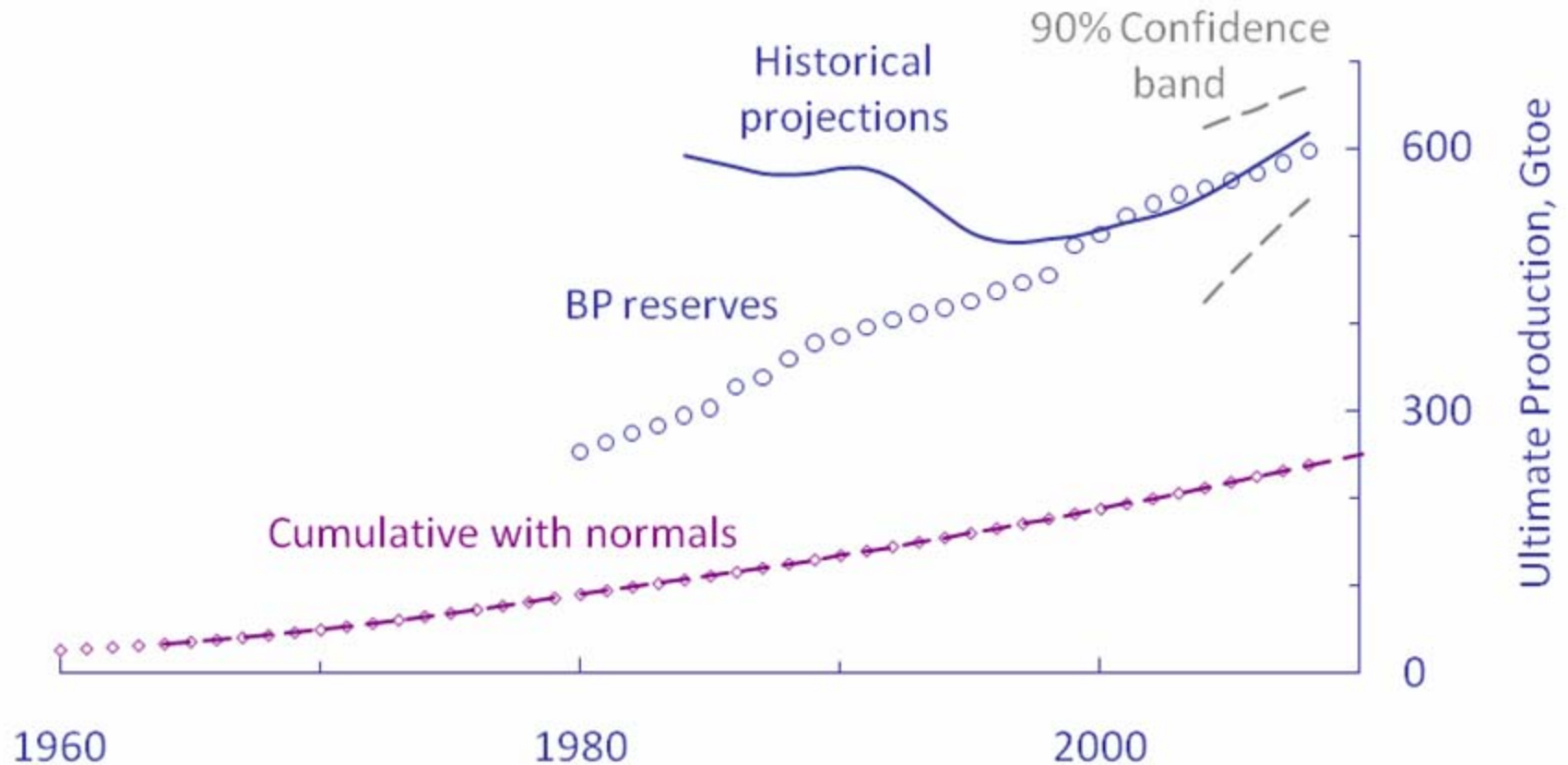
- The USGS/MMS assessment, 385Gb, implies an extraordinary break with history

World Oil and Gas Production



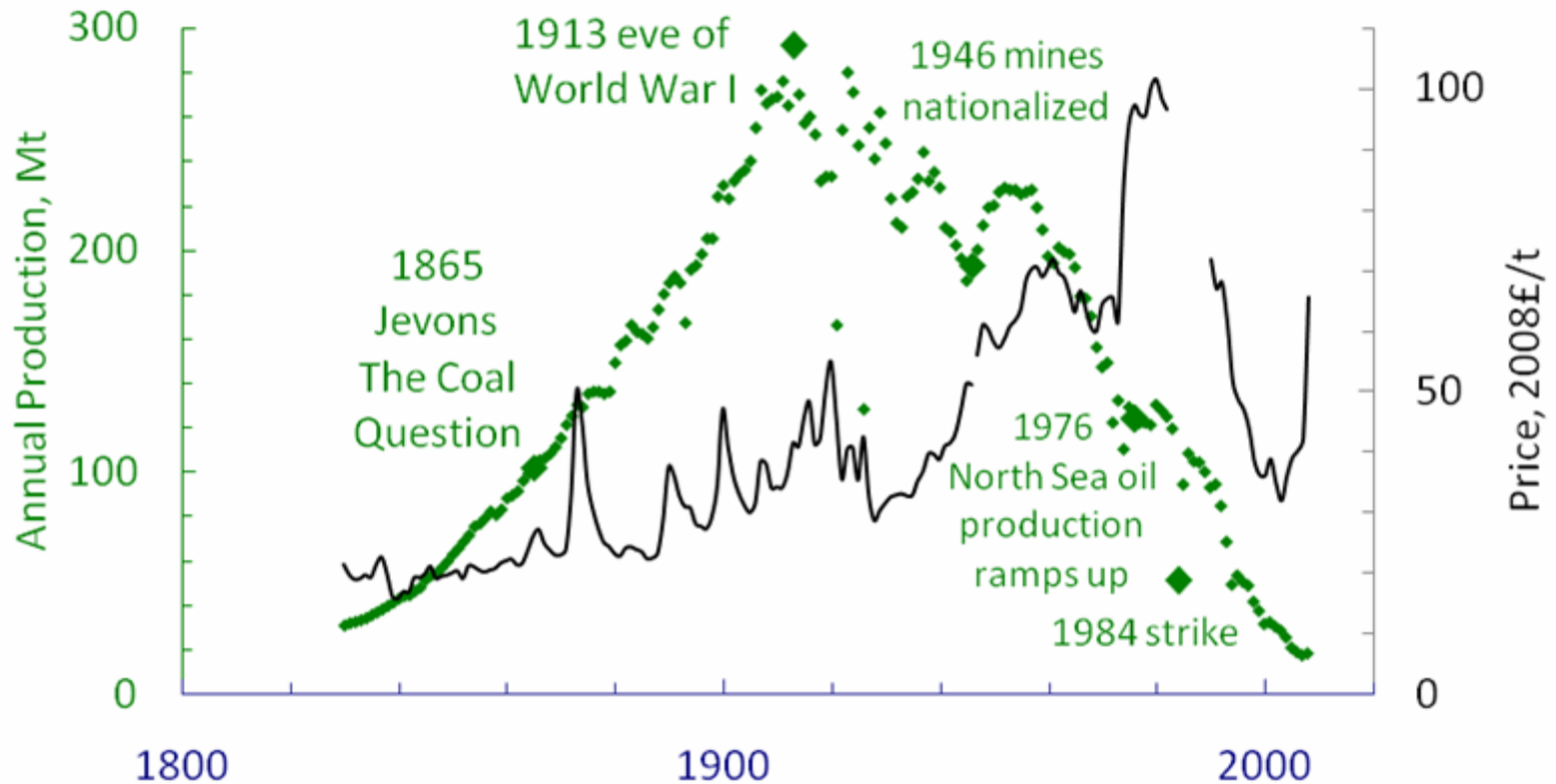
- 7.33 barrels of oil = 1 metric ton, toe = metric tons of oil equivalent
- Natural gas added as the energy equivalent

Confidence Band for Historical Projections



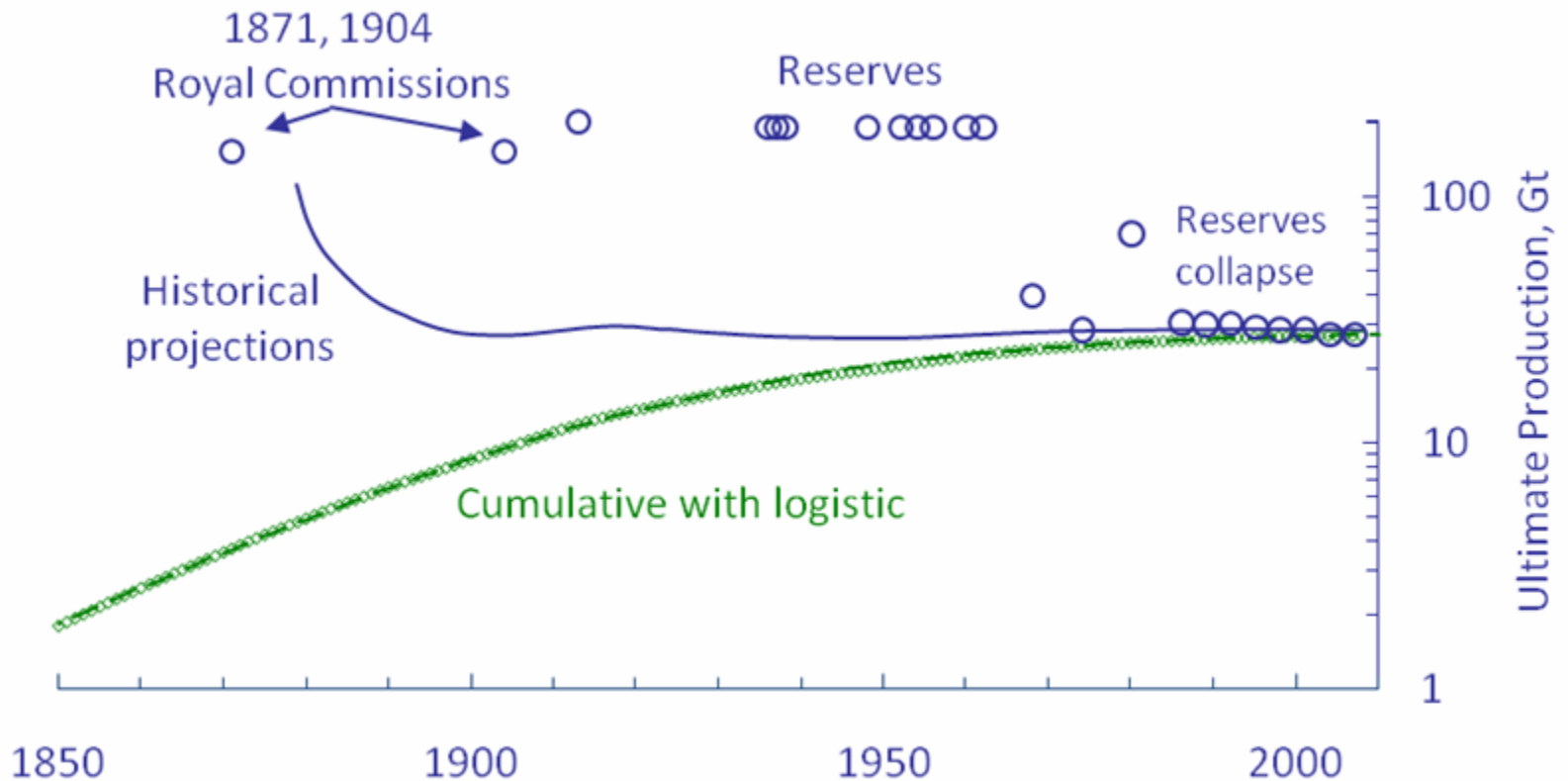
- Confidence band from 400 replications
- Current confidence interval is 541 to 669Gtoe

UK Coal Production



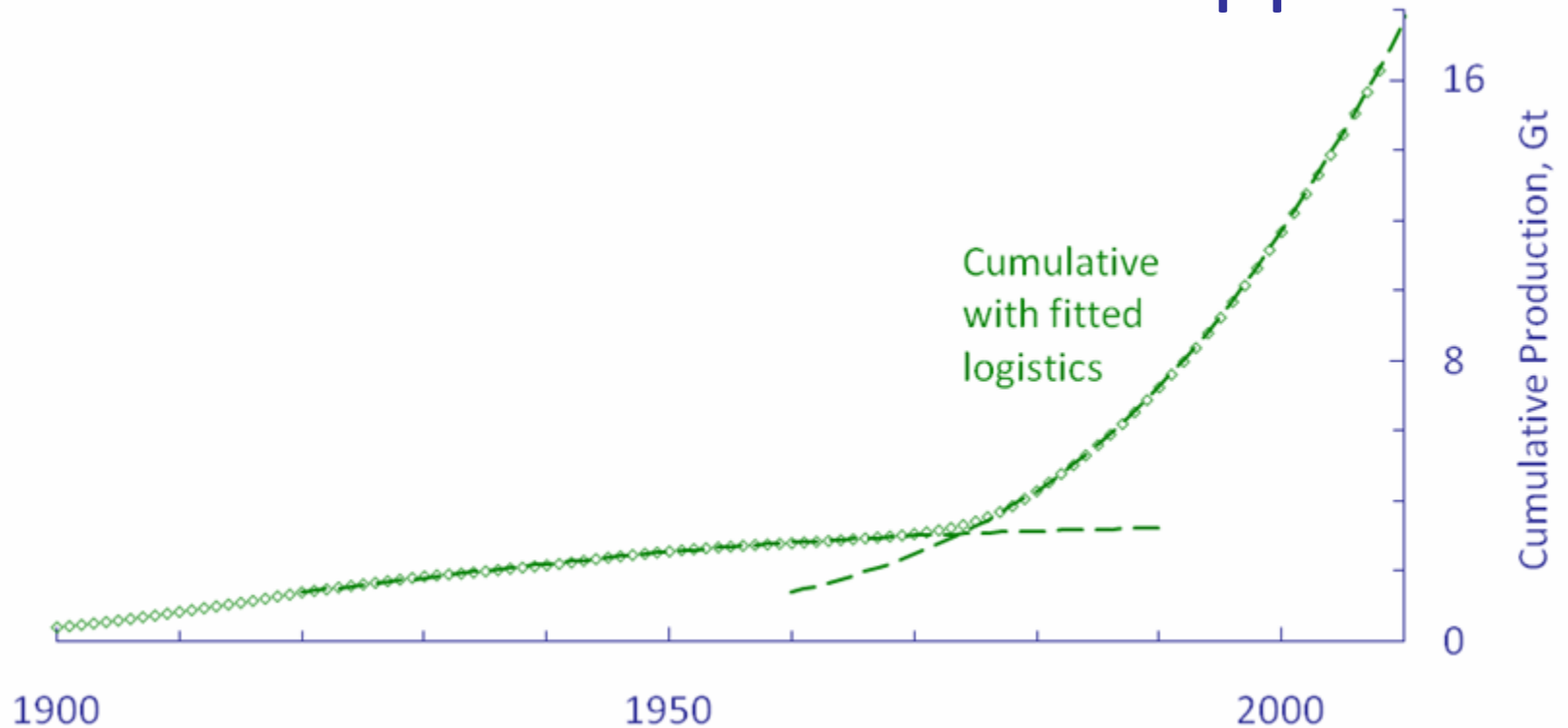
- Mt = millions of metric tons
- Production is now 16 times less than the peak
- The average price after the peak is 2.4 times higher than before

Historical Projections for UK Coal



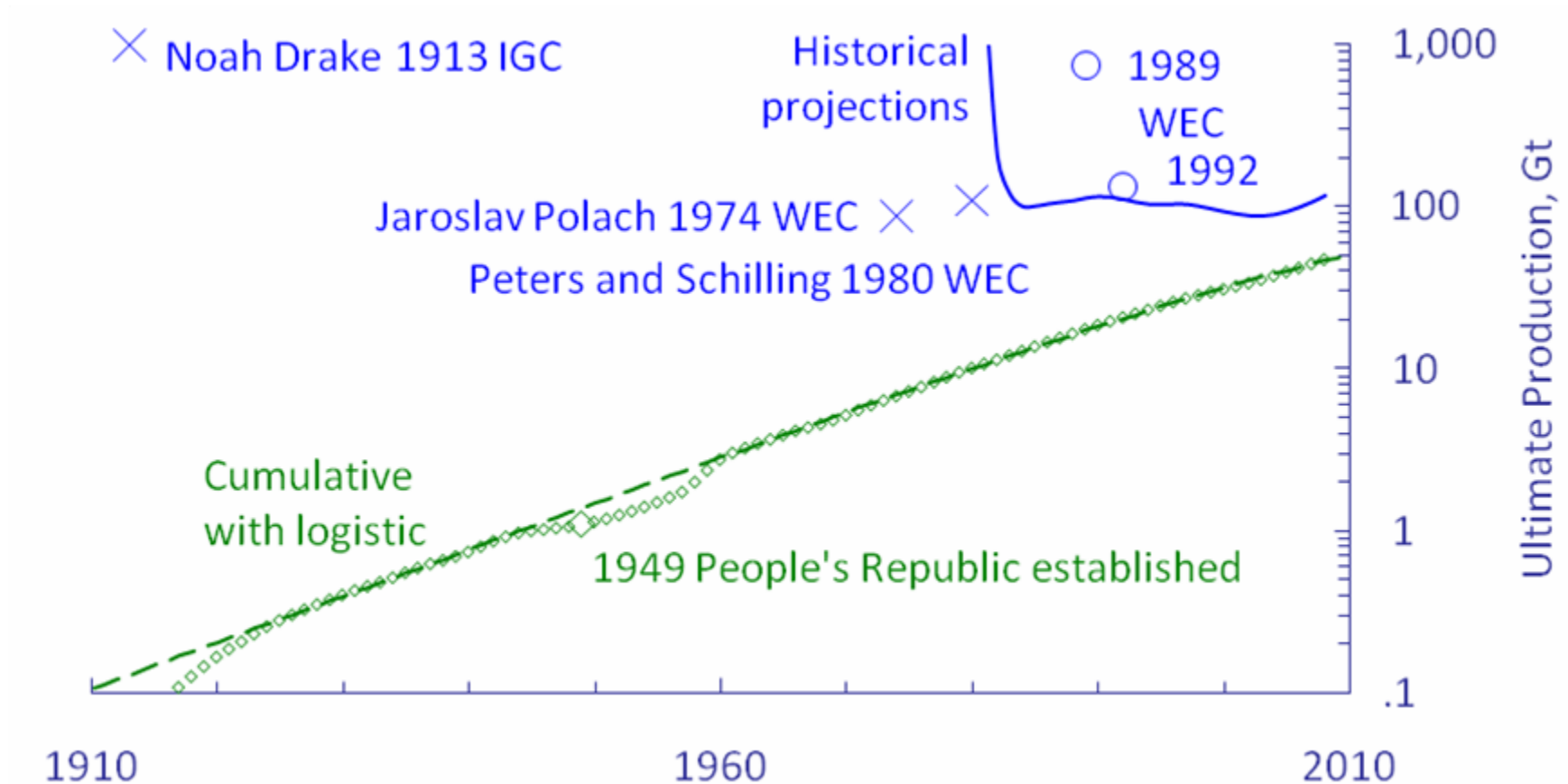
- Reserve numbers are available before projections stabilize
- Produced 18% of the 1871 Royal Commission reserves + cumulative
- Criteria were too optimistic — 1-ft seams, 4,000-ft depth

Coal West of the Mississippi



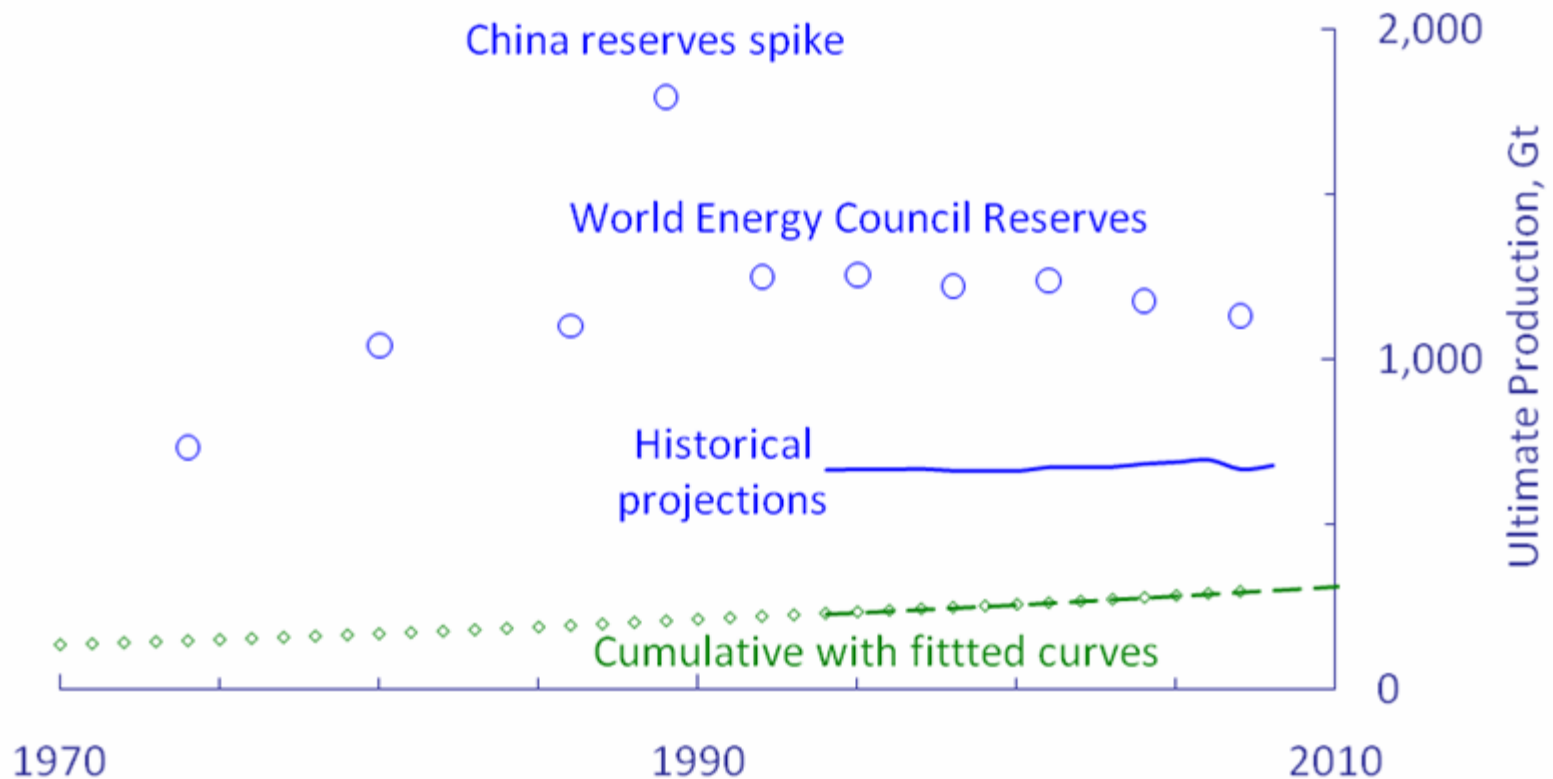
- Early production cycle for locomotives (3Gt ultimate) peaked in 1920
- New start after the 1970 Clean-Air Act, which encouraged the use of low-sulfur coal
- Maximum residual in current fit is 22 days since 1978
- US coal reserves are 13 times smaller than they were in 1913

Historical Projections for Chinese Coal



- Reserves submitted to World Energy Council in 1989 and 1992 differ by 6:1
- Projection for ultimate is 117Gt (75% of reserves + cumulative)

Historical Projections for World Coal



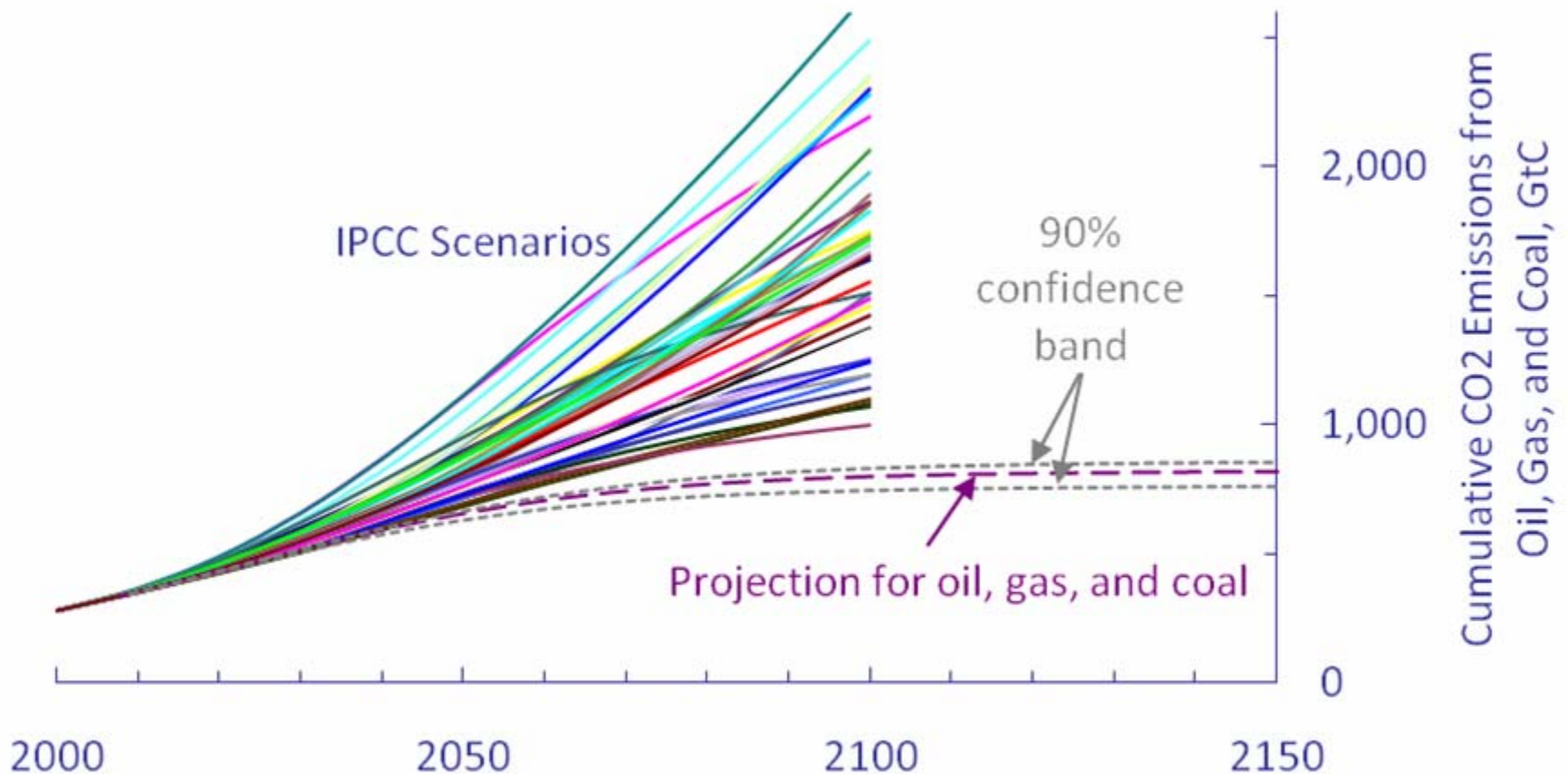
- 5% range from 1994 on — much tighter than for world oil and gas
- Projection for ultimate is 677Gt, 60% of reserves + cumulative
- IPCC range for production through 2100 is 354 to 3,400Gt (still growing in 2100)

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

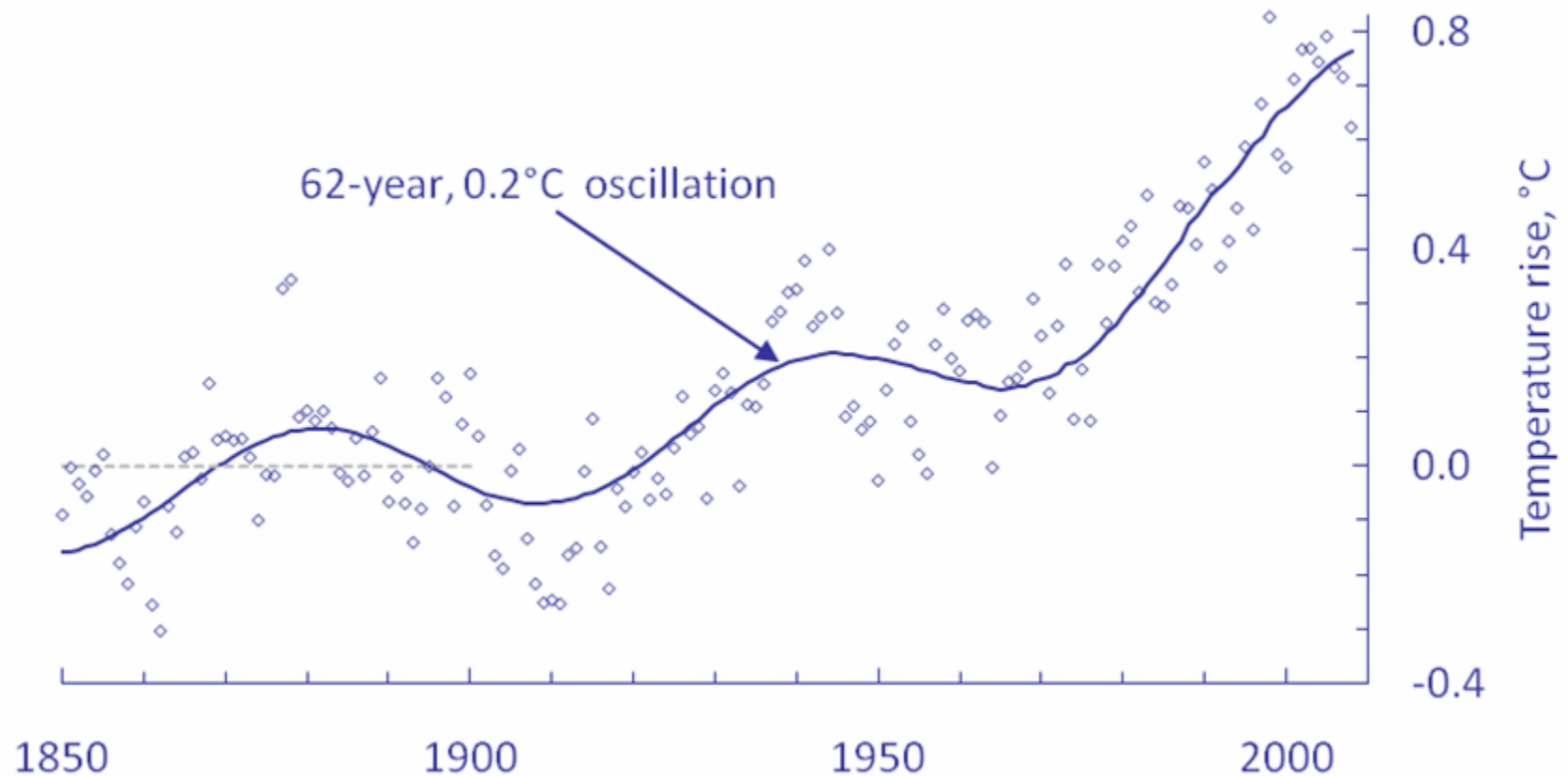
- The scenario report SRES (2000) references the 1995 and 1998 WEC surveys
- Downward trend in proved recoverable reserves was noted by Werner Zittel and Jorg Schindler of the German Energy Watch Group — trend toward reporting recoverable coal and coal at working mines
- The IPCC chose to use additional recoverable reserves and they also chose 1998 (3,368Gt) instead of 1995 (680Gt) — additional recoverable reserves are now 19 times smaller than in 1998

Carbon-Dioxide Emissions



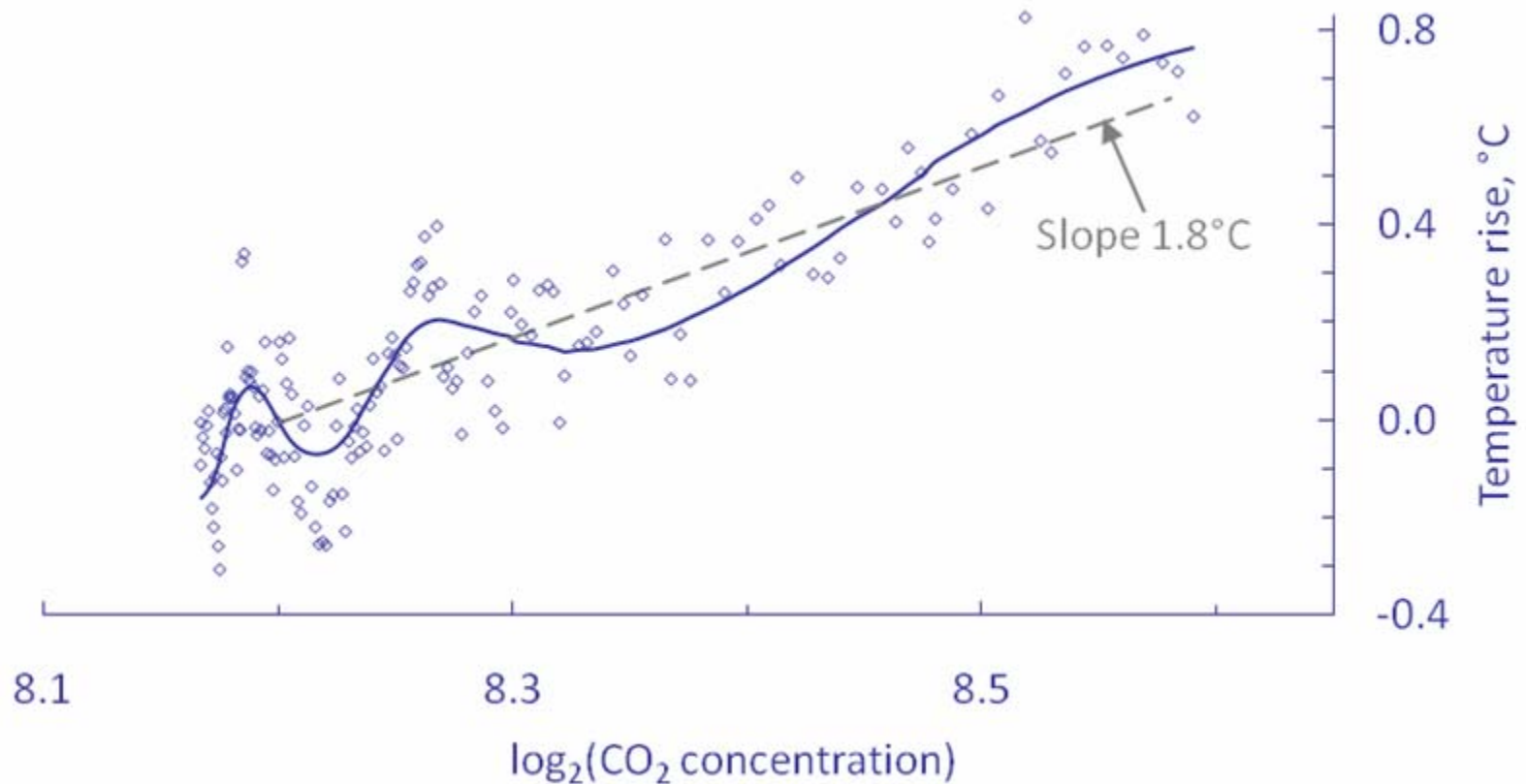
- Projection is less than any of the IPCC scenarios
- Using a physics-based model from Roger Schmitz, the top of confidence band for CO₂ concentrations is 448ppmv in 2065

Schlesinger/Ramankutty Model for Temperature



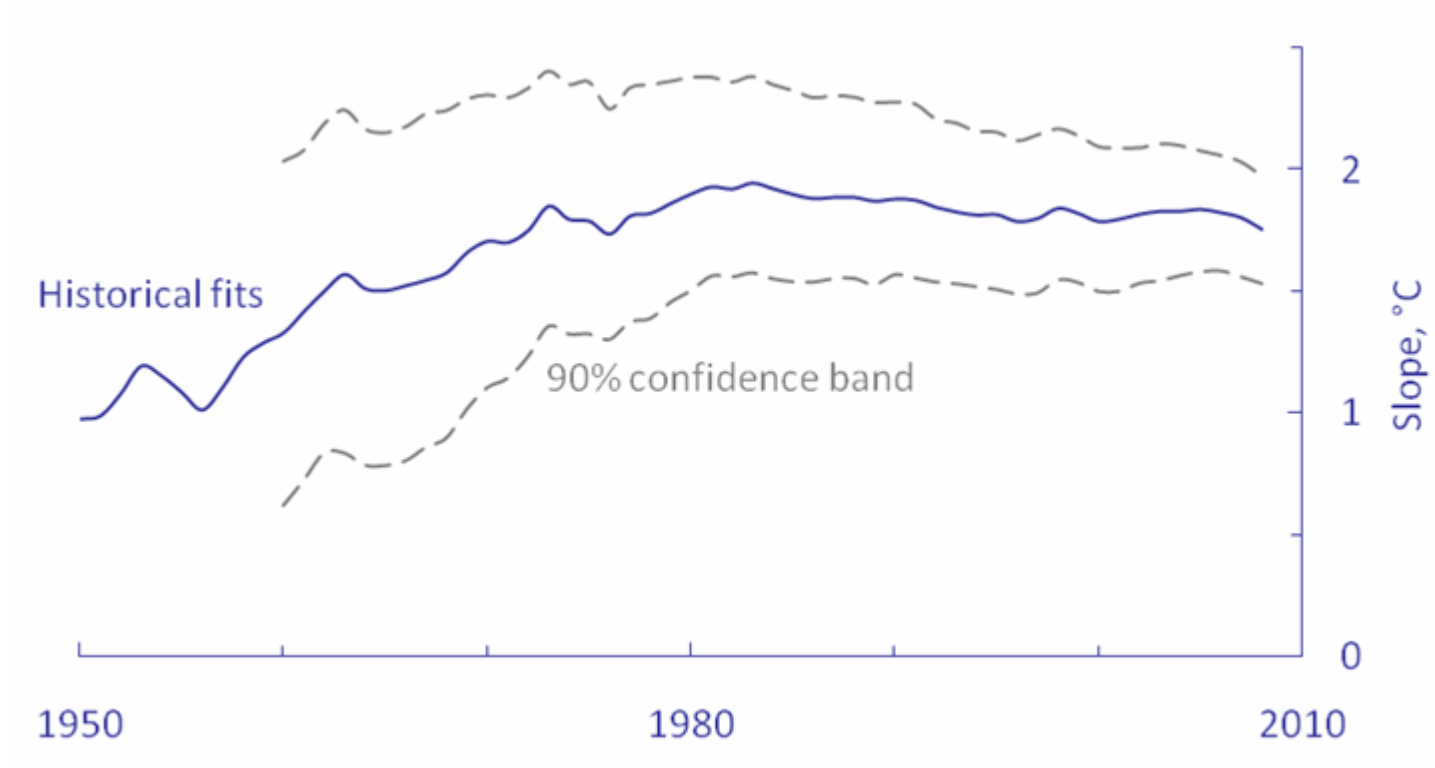
- Temperatures from the UK Hadley Centre, relative to the 1850-1900 average
- Schlesinger and Ramankutty identified the oscillation as the North Atlantic Multi-Decadal Oscillation

Schlesinger/Ramankutty Model for Temperature



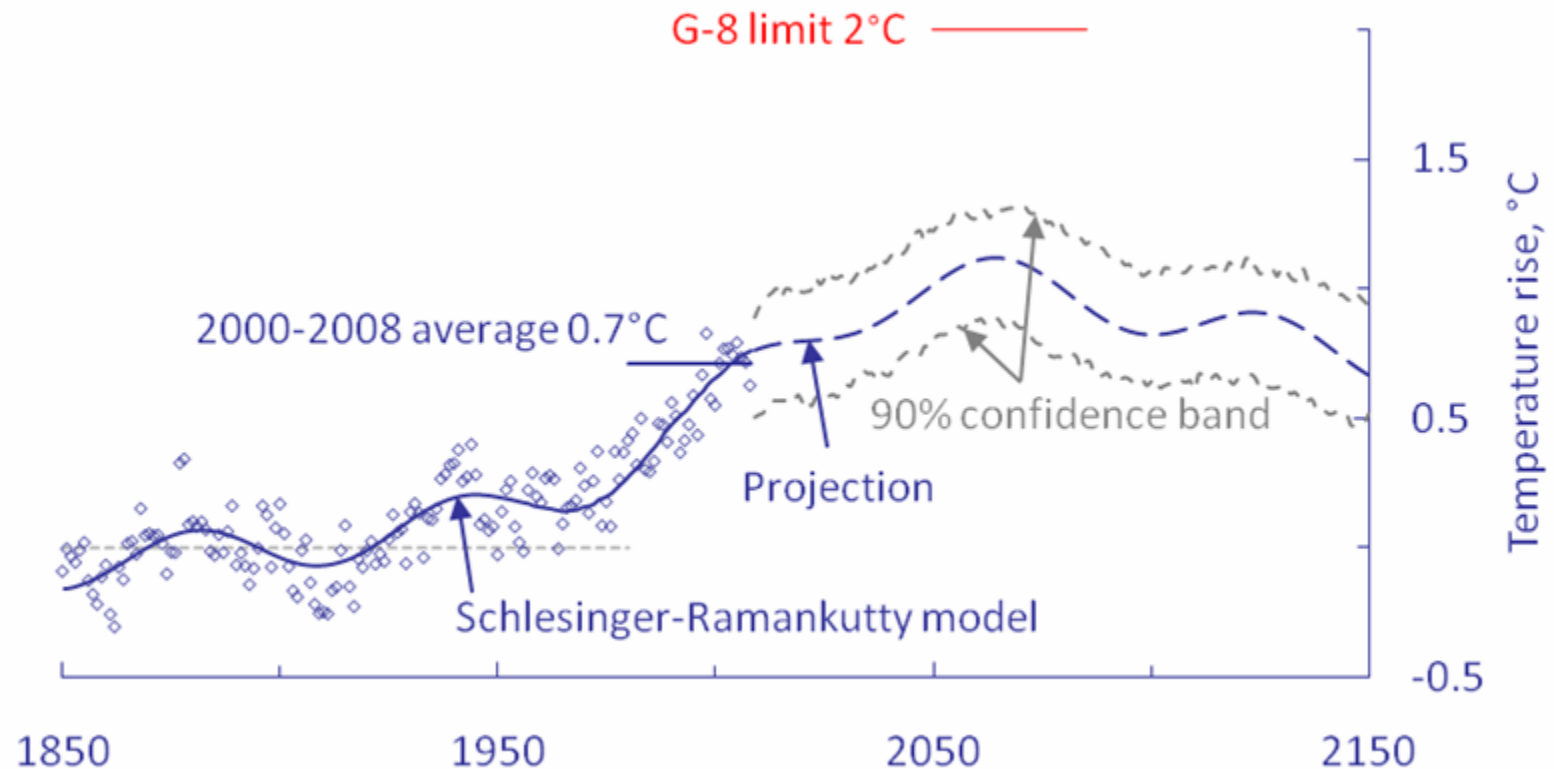
- The x-axis is logarithmic, base 2 — a change of 1 is a doubling of concentration
- This is a simpler version of their model — they treated aerosols separately
- Fits from 1958 on are to the Keeling Curve, earlier to the Schmitz model

Confidence Band for the Slope



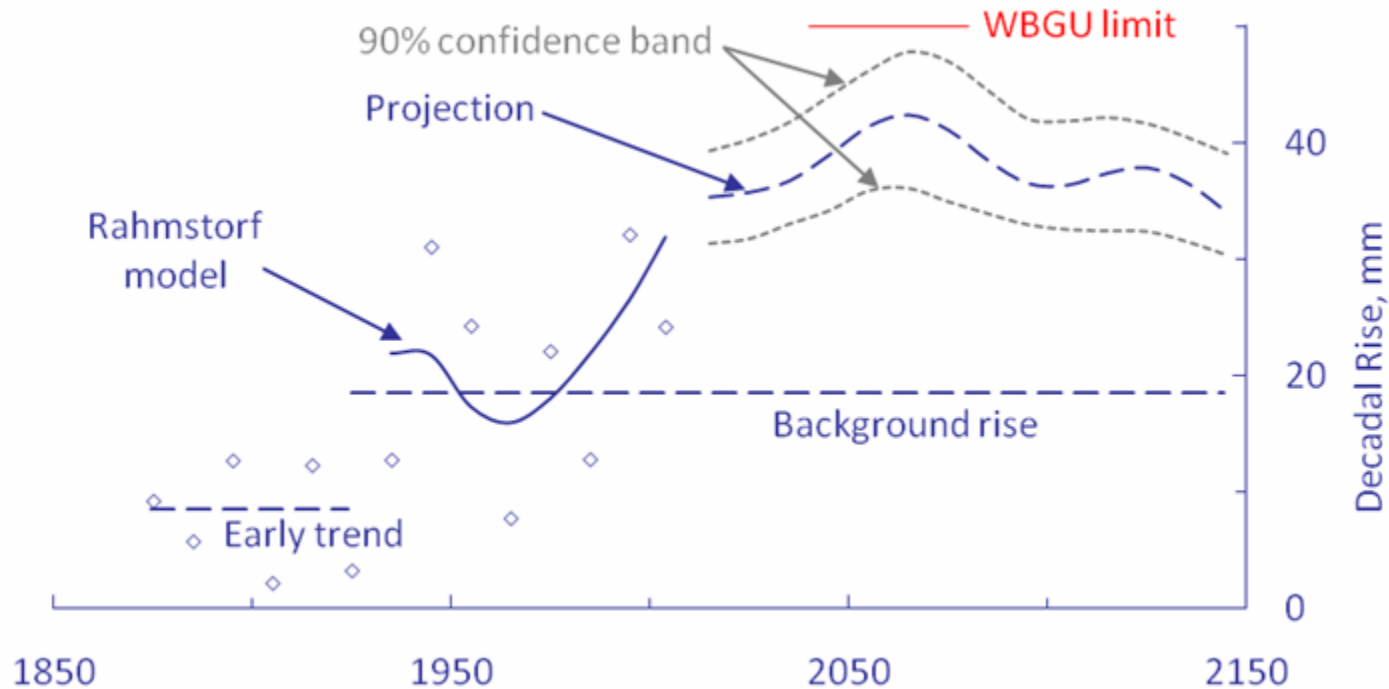
- This slope is not comparable to the IPCC sensitivity, where aerosols and greenhouse gases like methane and nitrous oxide are considered separately— but it has been stable since 1970
- Current confidence interval is 1.5 to 2.0°C

Confidence Band for the Temperature



- Future temperature rise associated with our projection for CO_2 is 0.35°C
- 90% range for historical short-term fluctuations 0.36°C ($\pm 0.18^\circ\text{C}$)
- Peak-to-peak oscillation is 0.19°C

Decadal Sea-Level Rise



- Peak of the confidence band is the decade of the 2060's with 48mm — 18mm per decade higher than the 30 mm during the last decade
- Rise rate associated with temperature is comparable to the background

Long Beach Subsidence — 9m!



Comparing Our Confidence Intervals with the IPCC Ranges

	Our 90% Confidence Interval	The IPCC Range
Ultimate oil, gas, and coal carbon emissions, GtC	762 to 859	999 to 2,683+ through 2099
Carbon dioxide level, ppmv	432 to 448 in 2065	500 to 980+ in 2099
Temperature, °C above the 2000-2008 average	0.1 to 0.6 in 2071	0.9 to 6.2+ for 2090-2099
Sea-level rise, mm per decade above the last decade	6 to 18 in 2060-2070	-15 to 67+ for 2090-2099

- I have added plus signs to the high sides of each IPCC range to indicate that for these scenarios, fossil-fuel production has not yet peaked by 2100, so a much higher value is implied after 2100

Summary

- US crude-oil production has been following a cumulative normal curve since 1901 — the 1995 USGS/2006 MMS oil assessment, 385Gb, is not consistent with the production history
- Ultimate estimates for coal from geological reserves are available early, but they are too high
- The projection for the world coal ultimate has been stable at around 60% of the reserves plus cumulative production (41% of future fossil-fuel carbon dioxide emissions)
- For both temperature and sea level, humanity's part of the future rise appears to be comparable to the natural changes