Tipping point analysis of atmospheric oxygen concentration

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- Interface between business, academia and government
- Science with impact: ensure that measurements are comparable and traceable to the same standard units of the System International (SI)
- 700 staff
“There is to be one measure of wine and ale and corn within the realm, namely the London quarter, and one breadth of cloth, and it is to be the same with weights.”
Tipping points: bifurcations and transitions in time series changes in system states
Tipping point toolbox (being developed since 2007)

- Anticipating (pre-tipping): early warning signals of tipping points
- Detecting (tipping): potential analysis
- Forecasting (post-tipping): PDF & potential analysis, recently added bayesian techniques
AD with four potentials

We generate artificial data using Euler scheme

\[ x_{t+\Delta t} \approx x_t - \frac{dU}{dx} \bigg|_t \cdot \Delta t + (W_{t+\Delta t} - W_t) \]

\( W \) is a Wiener process

Potentials:

\[ U(z) = z^2 \]
\[ U(z) = z^4 - 2z^2 \]
\[ U(z) = z^6 - 4.5z^4 + 5z^2 \]
\[ U(z) = z^8 - 6.5z^6 + 13z^4 - 8z^2 \]

Potential contour plot at different time scales
Atmospheric oxygen concentration

Unit is the change of $\frac{O_2}{N_2}$ ratio in *per meg*, 0.0001% of decline of oxygen concentration, reference is based on tanks of air pumped in the mid-1980s stored in the US lab.
Model to test tipping

Data = global trend + seasonality + fluctuations

What kind of trend?

Is seasonality stable?

Are fluctuations stable?
Synchrosqueezing: wavelet-based seasonal trend
Detrended data: fluctuations

![Graph showing detrended oxygen concentration anomaly δ(O₂/N₂) for various locations.

Locations include:
- Alert, Canada
- Cold Bay, Alaska
- Cape Grim, Australia
- Cape Kumukahi, Hawaii
- La Jolla Pier, California
- Mauna Loa, Hawaii
- Palmer station, Antarctica
- American Samoa
- South Pole

X-axis: time [years]
Y-axis: oxygen concentration anomaly δ(O₂/N₂)
Early warning indicators
Potential analysis
Information criteria for model fit of annually averaged data
Likely:

Seasonality is stable

Fluctuations are stable

Trend is parabolic
Projection of oxygen decline

Uncertainties: modelling and technological

health
Issues
start

parabolic decline

exponential decline
Alarming increase in fertilisation - oxygen sink (Haber-Bosch) and soil depletion
Global GHG emissions

- Energy supply 26%
- Forestry 17%
- Agriculture 14%
- Transport 13%
- Industry 19%
- Waste and wastewater 3%

Energy sink

Oxygen sink

IPCC

Tipping point

Global Fossil Carbon Emissions

- Total
- Petroleum
- Coal
- Natural Gas
- Cement Production

Million Metric Tons of Carbon / Year
1800 1850 1900 1950 2000

7000 6000 5000 4000 3000 2000 1000
Hydrogen cars: dual-fuel BMW 7

Two fuel tanks
170 litres of liquid hydrogen: driving range 200 km;
73 litres of petrol: driving range 480 km

This technology uses about 2.7 times less volume of oxygen for combustion in hydrogen mode than in petrol mode.

Most of modern hydrogen generation is not green!
(steam reforming of hydrocarbons at high temperature; also hydrolysis)

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

Technology with double sink of oxygen
Even when oil and gas will not be used for energy, they will be used for materials synthesis.
Possible collaboration in a publishing project

➢ To engage experts from various fields: geochemistry, physiology, wildfires and combustion

➢ To assess the oxygen decline time scale and impact

“The future of the atmospheric oxygen”?
Topics to address

- Measurement techniques and standardisation
- Derivation of long-term trend of oxygen from GCMs (100-200 years)
- Physiological impact of oxygen decline
- Long-term projections of oxygen under various scenarios of demographics and consumption development
- Assessment of impact of modern industrial technologies
- Raising social awareness of the oxygen decline
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The idea needs communal effort and support!

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Thank you
Early warning signal model

Series is approximated by an AR(1) process, and exponential decay of the auto-correlation function (ACF) is estimated. Thus ACF-indicator $c$ is defined; its gradual trend towards value 1 indicates critical behaviour.

$$y_{n+1} = cy_n + \sigma \eta_n,$$
$$c = \exp(-\kappa \Delta t), \kappa \text{ is decay rate}$$ ($\kappa = 0 \text{ when } c = 1$)
Artificial data with increasing memory
Livina et al, Physica A, 2012

When ACF-indicator reaches critical value 1, DFA-indicator is still capable to reflect the variability in the variance
Potential analysis model

\[ \dot{z}(t) = -U'(z) + \sigma \eta \]

\[ U(z) = a_4 z^4 + a_3 z^3 + a_2 z^2 + a_1 z \]

double-well potential

Kwasniok & Lohmann, Phys Rev E, 2009
Livina et al, Climate of the Past 2010
Potential vs Probability Density Function (PDF)

Fokker-Planck equation

$$\partial_t p(z, t) = \partial_z [U'(z) p(z, t)] + \frac{1}{2} \sigma^2 \partial^2_z p(z, t)$$

$$p(z) \approx \exp[-2U(z) / \sigma^2]$$

If we assume that the considered subset of data is stationary, then

$$U = -\frac{\sigma^2}{2} \log p_d$$

bimodal histogram $\iff$ double-well potential
GRIP & NGRIP temperature proxies

$\delta^{18}O$ data: bifurcation at 25-28 kyr BP

(Livina et al. Climate of the past. 2010)

GICC05 time scale, resolution 20yr

Calcium data: bifurcation at 27-28 kyr BP

Annual resolution
Potential forecast algorithm

Livina et al, Physica A 2013

- Collect coefficients of Chebyshev approximation of PDF in sliding windows
- Extrapolate series of the coefficients
- Reconstruct forecast PDF
- Simulate time series from the obtained PDF (rejection sampling)
- Sort the series according to historic data (taking into account seasonality)

Oxygen period of observations is short, horizon forecast long: other techniques are necessary