Climate Change and Exoplanet Sciences

what can they learn from each other?

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Exoplanets: Searching for a Needle in a Haystack...

Climate Change: Can’t see the Wood for the Trees
Optimizing Model Complexity for the Problem

Temptation to empirically fit models to data

Optimal Predictability?

Theoreticians on the loose!!

No. of Observations

Model Complexity
Recent Climate Change on Earth
Evidence of Global Climate Warming

10 warmest years all since 1997
2001-2007 were 7 of the 8 warmest years on record
1998 and 2005 the two warmest years on record
Greenhouse Gas Concentrations

Carbon dioxide: 33% rise  
Methane: 100% rise

Source: IPCC
Recent CO$_2$ Increase in the Context of the last 400 kyr
Recent $\text{CO}_2$ Increase in the Context of the last 400kyr
Svante Arrhenius (1859-1927)

- First to estimate the sensitivity of the Earth’s climate to atmospheric carbon dioxide.
- Estimate of 5-7°C for a doubling of CO$_2$ isn’t too far from current estimates (1.5-4.5°C)!
XXXI. On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. By Prof. SVANTE ARRHENIUS.

1. Introduction: Observations of Langley on Atmospherical Absorption.

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier ‡ maintained that the atmosphere acts like the glass in a hot house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet §; and Langley was by some of his researches led to the view, that ‘the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200 °C., if that atmosphere did not possess the

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December 1895. Communicated by the Author.

† “Heat a mode of motion,” 2nd ed. p.405 (Lond.,1865).
§ Compress rendus, t. vii. p41 (1838).

CO$_2$ Greenhouse Effect at the Molecular Level

Absorption by CO$_2$ Assymmetric Stretching Mode at 4.25 $\mu$m
Atmospheric Absorption

CO$_2$ Assymmetric Stretching-mode

CO$_2$ bending-mode

A. BLACK BODY CURVES

B. WAVELENGTH $\mu$

SUN

EARTH

ABSORPTION %

0 20 40 60 80 100

$\text{O}_2$ $\text{O}_3$ $\text{H}_2\text{O}$ $\text{CO}_2$ $\text{N}_2\text{O}$ $\text{H}_2\text{O}$ (rotation)
Future Climate Change on Earth:

Uncertainty in Predictions and Feedbacks
Predicted Pattern of Global Warming

SRES A1B 2000–2009
Uncertainty in Future Climate Change

Range of Global Warming by 2100

Intergovernmental Panel on Climate Change (IPCC), 2007
Climate Sensitivity to Doubling CO$_2$ remains uncertain….

Due to uncertainties in climate feedbacks….

Murphy et al., 2005
Simple Linear Conceptual Model

Global warming, $\Delta T$ (K), due to radiative forcing, $\Delta Q$ (W m$^{-2}$):

$$C. \frac{d\Delta T}{dt} + \lambda. \Delta T = \Delta Q$$

where $\lambda$ depends on climate feedbacks

where $\Delta Q$ depends on the changing concentrations of greenhouse gases and aerosols (particulates), as well as natural factors such as solar variability etc.

where $\lambda$ depends on climate feedbacks
Radiative Forcing of Climate 1750-2005

Human Factors Dominate

IPCC 2007
Consider long-term response to an initial perturbation, $\Delta T_0$: 

$$
\Delta T_{eq} = \Delta T_0 \left\{ 1 + g + g^2 + \ldots \right\}
$$

$$
= \Delta T_0 / \{1 - g\} \quad \text{for } |g| < 1
$$

- Positive feedback for $g > 0$
- Negative feedback for $g < 0$
- “Runaway” feedback/ linear instability for $g > 1$
Examples of Climate Feedbacks on Earth

- Water vapour feedback
- Snow/sea-ice albedo feedback
- Cloud feedbacks
- Ocean circulation changes
- Atmospheric circulation changes
- Carbon cycle feedbacks
- Lapse-rate feedback
Snow-Albedo Feedback

Decrease in Albedo increases sunlight absorbed and Increases Temperature

Increase in Temperature melts snow and decreases snow cover extent

Decrease in snow cover extent decreases the brightness ("albedo") of the surface

Overall sign of feedback loop is positive
Diagnosis of GCM Feedbacks

Water Vapour Feedback, $-\lambda_{WV}$

Snow albedo Feedback, $-\lambda_A$

Cloud Feedback

IPCC 2007
“Cloud Feedbacks (particularly from low clouds) remain the largest source of uncertainty” in climate projections.
Diagnosis of GCM Feedbacks

Feedback Gain \( \sim 0.7 \)

Positive Feedback

Negative Feedback
Viewing the Earth as an Exoplanet:

Would it be possible to detect Human Influence?
Author of the original Gaia hypothesis “that supposed the Earth to be kept at a state favourable for life by the living organisms”.

Based partly on the observation that Earth’s atmosphere has been kept far from equilibrium by life.
Life keeps the atmosphere from chemical equilibrium on Earth.

...but does it have to on other planets?

Earth’s atmosphere has ~100 times more oxygen, and ~1000 times less carbon dioxide than if it was in a chemical equilibrium state without life.

Lenton, 1998
Natural factors cannot explain recent warming
Recent warming can be simulated when man-made factors are included.
Atmospheric Energy Balance on Earth

TOA Fluxes
Development of the Hadley Centre models

Off-line model development

Strengthening colours denote improvements in models

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HadGEM2-ES Simulation: Reflected SW at TOA

Historical Simulation

Pre-industrial Control Simulation
Aerosol and Greenhouse Gases have increased together until now, but are now decoupling.

Andreae et al., 2005
Aerosol Pollution has had a large impact on climate

Pollution from ships giving brighter clouds
HadGEM2-ES Simulation: Reflected SW at TOA

- Pre-industrial Control Simulation
- Historical Simulation
- RCP8.5 Wm\(^{-2}\) Scenario

Trend ~ -0.5% per decade
HadGEM2-ES Simulation: Outgoing LW at TOA

Outgoing LW (W/m²) vs Year

Trend ~ 0.1% per decade
HadGEM2-ES Simulation

Outgoing LW + Outgoing SW

C. \( \frac{d\Delta T}{dt} = \Delta Q - \lambda \cdot \Delta T \)
World Energy Consumption

About 15 TW of total power consumed globally implies about 0.1 Wm$^{-2}$ of waste heat (assuming an efficiency of 30%) - so we will become even less visible as we become more sustainable!
Observed Change in Outgoing LW Spectra

Harries et al., 2001
Unifying Principles to Simplify Models of Climate Systems
Maximum Entropy Production: Application to the Climate System

- 1960s: Ed Lorenz suggests that the climate system maximises "work". (E. Lorenz, 1960)

- 1970s: Garth Paltridge develops successful climate model based on the assumption that heat transports maximise the rate of entropy production. (Paltridge 1975; 1978)

- 2003: Ralph Lorenz et al. show that MEP is consistent with the observed equator-to-pole temperature contrasts on Titan and Mars (as well as Earth). (R. Lorenz et al., 2003).
Equator-Pole heat flux  \( F = 2D (T_0 - T_1) \)

D chosen to maximise the rate of Entropy Production

Entropy Production Rate = \( F \{ 1 / T_1 - 1 / T_0 \} \)
2-box MEP model including dynamics


Solve for flow $U$, $\theta$ with surface drag $C_D$ as free parameter
Maximum Entropy Production: Application to the Climate System

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- 2003: Roddy Dewar derives the MEP principle from Information Theory, in a manner similar to the information approach to the second law of thermodynamics.  
  (Dewar, 2003, 2005).
“Dangerously Seductive”
...but sometimes it’s nice to be seduced...
Atmospheric Energy Balance on Earth

Earth’s Energy Balance

TOA Fluxes

Turbulent Flux
Leaky Greenhouse Model + Turbulent Flux by MEP

Atmosphere absorbs a fraction $\varepsilon$ of the radiation from the surface

$$\text{(1-}\varepsilon) \sigma T_s^4$$

Atmosphere emits with emissivity $\varepsilon$

$$\varepsilon \sigma T_a^4$$

Absorbed SW Radiation $R_s$

Surface radiates as a blackbody

Surface, $T_s$

Atmosphere, $T_a$

Turbulent Heat Flux $F$
Equations of the “Model”

Top-of-the-atmosphere energy balance:

\[ R_s = (1-\varepsilon) \sigma T_s^4 + \varepsilon \sigma T_a^4 \]

Surface energy balance:

\[ R_s + \varepsilon \sigma T_a^4 = \sigma T_s^4 + F \]

Assume \( F \) maximises the rate of entropy production:

\[ \frac{dS}{dt} = F \{1/T_a - 1/T_s\} \]
Entropy Production vs Turbulent Flux and Emissivity
Turbulent Transfer Coefficient at MEP versus Emissivity
Simple Models for Turbulent Flux

![Graph showing turbulent flux vs. IR optical depth.]

- **Turbulent Flux / Absorbed SW**
- **IR Optical Depth**

2-box MEP Solution

- **Lorenz & McKay 2003**
- **Osawa et al. 1997**
Simple Models for Turbulent Flux

Turbulent Flux / Absorbed SW

IR Optical Depth

2-box MEP Solution

Earth

Mars

Osawa et al. 1997

Lorenz & McKay 2003
Climate Tipping Points
United Nations Framework Convention on Climate Change (UNFCCC)

“The ultimate objective [is].... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system...”

Introduces the notion of “Dangerous” Climate Change...

....but how can this be defined ?
Tipping Points (Lenton et al., 2008)
Planetary Circulation Regimes and Climate Tipping Points

Peter Read, this conf.
What can they learn from each other?

- Climate/Planetary Atmosphere Models are now converging, so modelling techniques can be shared.

- Climate Scientists can provide insights into the uncertainties in models.

- Planetary Scientists can provide insights into the diversity of planetary “climates”, which may help us to understand the possible future (and past) development of Earth’s climate, and identify “tipping points”.

- Together we need to develop more robust representations of climate processes. Developments in MEP principles may help in this respect.
Together we can have fun searching for Needles in the Haystack!
Planets in Advection vs Rotation Space

Dynamics affect MEP state.

Rotation matters.
Energy balance (schematic)
Application of MEP Principle to Titan

Observed Equatorial Temperature

Modelled Polar and Equatorial Temperatures

Observed Polar Temperature

Entropy Production Rate due to equator-pole heat transport

Maximum Entropy Production (MEP) fits observations

Lorenz et al., 2003