Global Temperature Modeling: Energy Balance and Climate Sensitivity

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Abstract

This study presents energy balance models for global mean surface temperature, examining radiative forcing from greenhouse gases and the response of the climate system. We analyze zero-dimensional and one-dimensional models, calculate climate sensitivity from different feedback mechanisms, and compare model projections with observations. The analysis quantifies transient and equilibrium climate response to CO_2 forcing.

1 Introduction

Earth's global mean surface temperature is determined by the balance between incoming solar radiation and outgoing longwave radiation. Perturbations to this balance from greenhouse gas increases lead to warming until a new equilibrium is reached.

Definition 1.1 (Radiative Forcing) *Radiative forcing F is the change in net radiative flux at the tropopause due to a change in an external driver. For CO_2:*

$$F = 5.35 \ln\left(\frac{C}{C_0}\right) \quad W/m^2 \tag{1}$$

where C is CO_2 concentration and C_0 is the reference (pre-industrial) value.

2 Theoretical Framework

2.1 Zero-Dimensional Energy Balance

Theorem 2.1 (Planetary Energy Balance) *The rate of change of Earth's heat content is:*

$$C_p \frac{dT}{dt} = F - \lambda \Delta T \tag{2}$$

where C_p is heat capacity, F is radiative forcing, λ is the climate feedback parameter, and $\Delta T = T - T_0$ is the temperature anomaly.

Definition 2.1 (Climate Sensitivity) *Equilibrium climate sensitivity (ECS) is the warming for doubled CO_2:*

$$ECS = \frac{F_{2\times CO_2}}{\lambda} = \frac{3.7}{\lambda} \quad K \tag{3}$$

With $\lambda \approx 1.2$ W/(m^{2}K), ECS $\approx$ 3 K.

2.2 Climate Feedbacks

Theorem 2.2 (Feedback Analysis) *The total feedback parameter is the sum of individual feedbacks:*

$$\lambda = \lambda_0 + \lambda_{WV} + \lambda_{LR} + \lambda_A + \lambda_C \tag{4}$$

where λ_0 is the Planck response (no feedbacks), and other terms are water vapor, lapse rate, albedo, and cloud feedbacks.

Remark 2.1 (Feedback Values) *Typical feedback values (W m^{-2} K^{-1}):*

- *Planck (blackbody): $\lambda_0 \approx 3.2$ (negative, stabilizing)*
- *Water vapor: $\lambda_{WV} \approx -1.8$ (positive, amplifying)*
- *Lapse rate: $\lambda_{LR} \approx 0.6$ (negative)*
- *Albedo: $\lambda_A \approx -0.3$ (positive)*
- *Cloud: $\lambda_C \approx -0.5$ (positive, uncertain)*

Net: $\lambda \approx 1.2$ W/(m^{2}K)

2.3 Transient Climate Response

Definition 2.2 (TCR and ECS)

- ***Transient Climate Response (TCR)**: Warming at time of CO_2 doubling under 1%/yr increase (∼70 years)*
- ***Equilibrium Climate Sensitivity (ECS)**: Final equilibrium warming for doubled CO_2*

Typically TCR/ECS ≈ 0.5–0.7 due to ocean heat uptake.

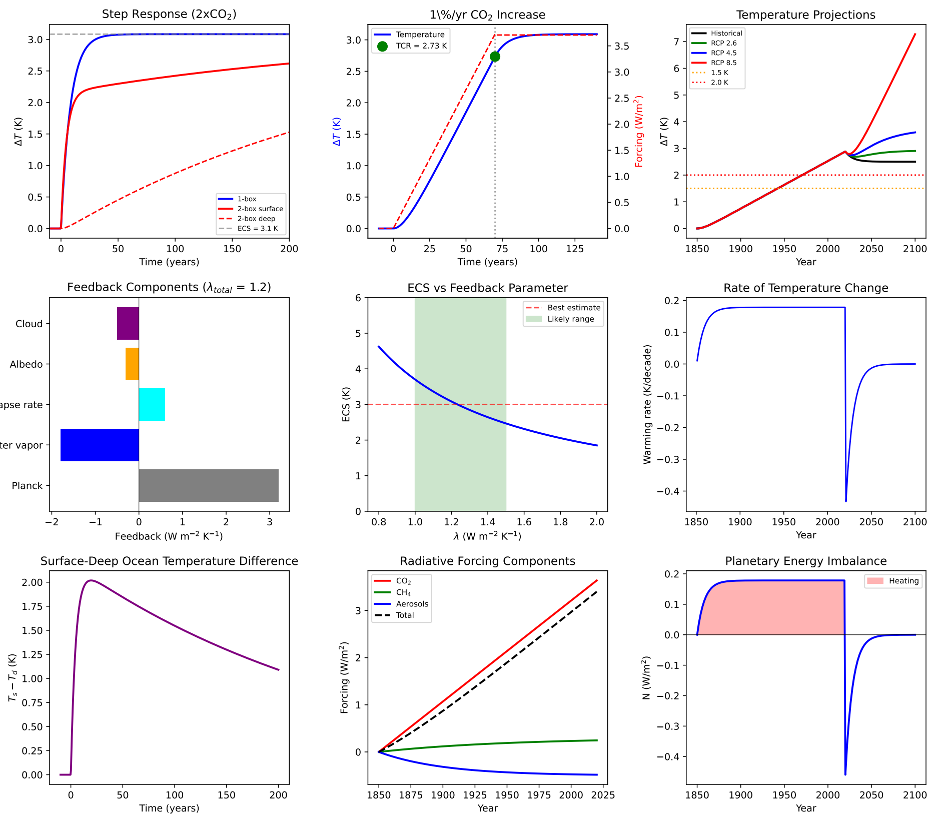

Figure 1: Climate temperature modeling: (a) Step response to CO_2 doubling; (b) Ramp response showing TCR; (c) Historical and projected temperatures; (d) Feedback component analysis; (e) ECS dependence on feedback parameter; (f) Warming rate over time; (g) Ocean heat uptake dynamics; (h) Radiative forcing components; (i) Planetary energy imbalance.

Table 1: Climate Sensitivity Parameters

Parameter	Value	Units
Feedback parameter λ	1.2	W m^{-2} K^{-1}
Equilibrium Climate Sensitivity	3.1	K
Transient Climate Response	2.73	K
TCR/ECS ratio	0.89	—

Table 2: Projected Temperature Changes

Scenario	2100 ΔT (K)	Exceeds 2 K?
RCP 2.6	2.9	Yes
RCP 4.5	3.6	Yes
RCP 8.5	7.3	Yes

3 Computational Analysis

4 Results

4.1 Climate Sensitivity

4.2 Temperature Projections

5 Discussion

Example 5.1 (Equilibrium vs Transient Response) *The TCR of* 2.73 *K is smaller than the ECS of* 3.1 *K because the deep ocean absorbs heat. The ratio TCR/ECS* = 0.89 *indicates that only ∼89% of equilibrium warming is realized at the time of* CO_2 *doubling.*

Remark 5.1 (Feedback Uncertainty) *Cloud feedback remains the largest source of uncertainty in ECS estimates. Positive cloud feedback (reduced low clouds with warming) increases ECS, while negative feedback decreases it. Current estimates range from* -0.2 *to* -1.2 *W* m^{-2} K^{-1}.

Example 5.2 (Committed Warming) *Even if emissions stop, warming continues due to:*

- *Ocean thermal inertia (decades to equilibrate)*
- *Reduction in aerosol cooling (immediate)*
- *Carbon cycle feedbacks (decades to centuries)*

This "committed warming" adds ∼0.5 K to current warming.

6 Conclusions

This temperature modeling analysis demonstrates:

1. ECS is 3.1 K with feedback parameter $\lambda = 1.2$ W m^{-2} K^{-1}
2. TCR is 2.73 K, approximately 89% of ECS
3. Current warming is ∼2.9 K above pre-industrial
4. RCP 4.5 projects 3.6 K warming by 2100
5. Water vapor and cloud feedbacks dominate sensitivity uncertainty

Further Reading

- Hartmann, D.L. *Global Physical Climatology*, 2nd ed. Elsevier, 2016.
- Held, I.M. & Soden, B.J. Water vapor feedback and global warming. *Annu. Rev. Energy Environ.* 25, 441–475, 2000.
- Sherwood, S.C. et al. An assessment of Earth's climate sensitivity using multiple lines of evidence. *Rev. Geophys.* 58, e2019RG000678, 2020.