Title:
Penguin Thermoregulation and Collective Behavior in a Simulated Wind Environment

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Abstract
This simulation models the thermoregulatory behavior of emperor penguins in response to environmental factors such as air temperature, wind, and radiant heat from nearby individuals. Each penguin is represented as an agent that attempts to maintain its body temperature within a biologically plausible range by dynamically adjusting its position based on thermal gradients and crowd density. The model combines a heat transfer differential equation with agent-based movement rules to replicate clustering (huddling) behaviors and thermal homeostasis.

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1. Introduction

Emperor penguins exhibit collective thermoregulation through huddling, enabling them to survive extreme Antarctic conditions. This project simulates such behavior by treating each penguin as a dynamic cylinder with internal heat generation, heat loss to the environment, and radiative exchange with neighbors. The system uses both continuous and discrete modeling elements to simulate thermal evolution and agent motion in a wind-affected environment.

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2. Governing Differential Equation

Each penguin's body temperature evolves based on four mechanisms:

- **Heat loss to the cold air**
- **Convective heat loss due to wind**
- **Radiative heat gain from warmer neighbors**
- **Internal metabolic heating, increasing when body temperature deviates from optimum**

Let T(t) be the body temperature of a penguin at time t. The governing equation is:

$$\frac{dT}{dt} = -k_{air}(T - T_{air}) - k_{wind} v^{0.6} + Q_{body} + k_{rad} \sum_{j=1}^{n} \frac{max(0, T_j - T)}{d_{ij}^2 + epsilon}$$

Where:

- T_{air} is the ambient air temperature
- v is the local wind speed
- T_j is the temperature of neighboring penguins
- d_{ij} is the distance to neighbor j
- Q_{body} is the internal heat generation modeled as a sigmoid:

$$Q_{body} = k_{body} \frac{1}{1 + e^{-5(T_{opt} - T)}}$$

- Constants:
  - k_{air}, k_{wind}, k_{rad}, k_{body} are tunable coefficients
  - ϵ is a small constant to avoid division by zero

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3. Discretized Difference Equation
In the simulation, the equation is discretized using Euler's method:

$$T_{t+1} = T_t - \Delta t \cdot \left(k_{air}(T_t - T_{air}) + k_{wind} v^{0.6} - Q_{body} - k_{rad} \sum_{j=1}^{n} \frac{max(0, T_j - T_t)}{d_{ij}^2 + epsilon} \right)$$

Where Δt is the time step, and the summation is taken over the nearest neighbors within the perception radius.

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4. Movement Model
Penguins move according to thermal optimization rules:

- If too cold ($T < T_{opt}$), move toward warmer regions (i.e., climb temperature gradients)
- If too warm ($T > T_{opt}$), move away from neighbors
- If temperature exceeds survivable bounds, the penguin is removed (assigned a negative position)

Motion also accounts for:

- Repulsion if agents are too close (hard-stop distance)
- Recentering of the group by shifting all positions to maintain centrality in the grid

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5. Wind and Flow Field
Wind flow around each penguin is modeled as flow around a cylinder using potential flow approximations. The velocity field is summed over all penguins to compute local wind speeds.

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6. Summary
This simulation blends thermodynamics, fluid dynamics, and biologically inspired behavior to model collective adaptation in extreme climates. It allows for real-time visualization of how simple local rules can give rise to complex group-level strategies for survival.