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How do climate, vegetation and greenhouse gases interact in three simple models of an ocean–land planet?

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Following up on work of Rombouts & Ghil (Nonlin. Processes Geophys., 2015) and motivated by the subsequent use of their model in studies of exoplanet atmospheres (e.g., Alberti et al., Astrophys. J., 2017), we formulate and analyze three simple models for climate–vegetation interaction. The simplified planet we consider is characterized by a land surface that is partly vegetation covered and partly a desert, and an ocean that is partly open and partly sea ice–covered. In each one of the three models, a system of coupled ordinary differential equations describes the evolution of global atmospheric temperature, continental vegetation cover, and atmospheric concentration of carbon dioxide, based on their mutual feedbacks.

We first focus on the feedbacks that temperature and vegetation exert on each other via two processes: on the one hand, plant growth is conditioned by global temperature and affected by its fluctuations; on the other hand, terrestrial albedo, a strong regulator of global temperature, is conditioned by the fluctuating vegetation and sea-ice cover. The second model takes into account the atmospheric concentration in carbon dioxide that influences vegetation growth via photosynthesis and the global temperature via the greenhouse effect. Conversely, this concentration evolves according to the intensity of the carbon fluxes between the other components of the Earth system — lithosphere, hydrosphere and biosphere. In the third model, we consider two types of vegetation (biomes), and study their competition in covering the land, thus essentially augmenting J.E. Lovelock's Daisyworld model by the presence of a partially ice-covered ocean. In each model, we use numerical methods of bifurcation theory to determine the presence and stability of fixed points and of limit cycles that correspond to stationary climates and to periodic ones.