

Title: Radiative and dynamic controls of global scale energy fluxes

In this thesis I study the processes that control the global scale energy budget of the climate system and the fluxes of energy within the climate system using both models and data. I focus on three primary questions: (1) What determines the Earth's planetary albedo? (2) What determines the meridional heat transport in the climate system? (3) What controls the seasonal amplitude of energy fluxes on the equator-to-pole scale?

(1) Planetary Albedo

The planetary albedo is partitioned into a component due to atmospheric reflection and a component due to surface reflection by using shortwave fluxes at the surface and top of the atmosphere in conjunction with a simple radiation model. The vast majority of the observed global average planetary albedo (88%) is due to atmospheric reflection. Surface reflection makes a relatively small contribution to planetary albedo because the atmosphere attenuates the surface contribution to planetary albedo by a factor of approximately three. The global average planetary albedo in the ensemble average of the CMIP3 pre-industrial simulations is also primarily (87%) due to atmospheric albedo. The inter-model spread in planetary albedo is relatively large and is found to be predominantly a consequence of inter-model differences in atmospheric albedo, with surface processes playing a much smaller role despite significant inter-model differences in surface albedo. The CMIP3 models show a decrease in planetary albedo under a doubling of carbon dioxide -- also primarily due to changes in atmospheric reflection (which explains more than 90% of the inter-model spread). All models show a decrease in planetary albedo due to the lowered surface albedo associated with a contraction of the cryosphere in a warmer world, but this effect is small compared to the spread in planetary albedo due to model differences in the change in clouds.

(2) Meridional Heat Transport

The meridional heat transport (MHT) is expressed as the difference between the equator-to-pole contrast in absorbed solar radiation (ASR*) and outgoing longwave radiation (OLR*). As an example, in the Northern Hemisphere observations, the extratropics receive an 8.1 PW deficit of net solar radiation (ASR*) relative to the global average that is balanced by a 2.4 PW deficit of outgoing longwave radiation (OLR*) and 5.7 PW of energy import via the atmospheric and oceanic circulation (MHT). The inter-model spread of MHT in the CMIP3 simulations of the pre-industrial climate is primarily ($R^2 = 0.72$) due to differences in ASR* while model differences in OLR* are uncorrelated with the MHT spread. ASR* is partitioned into components due to the incident radiation at the top of the atmosphere and the equator-to-pole contrast of planetary albedo which is further subdivided into components due to atmospheric and surface reflection. In the observations 62% of ASR* is due to the meridional distribution of incident radiation, 33% is due to atmospheric reflection, and 5% is due to surface reflection. The inter-model spread in ASR* is due to model differences in the equator-to-pole gradient in planetary albedo that are primarily a consequence of atmospheric

reflection differences (92% of the spread) and is uncorrelated with differences in surface reflection. As a consequence, MHT in climate models is primarily determined by cloud reflection. These ideas are extended to simulations of anthropogenic global warming and paleoclimate states where it is found that changes in cloud reflection exert as profound an influence on MHT as even zeroth order changes in surface albedo.

(3) Seasonal energy fluxes

The seasonal amplitude of energy fluxes to the extratropics is driven by large variations in solar radiation that are primarily balanced by ocean heat storage anomalies; changes in meridional heat transport, emitted long wave radiation, and atmospheric heat storage play a decreasingly important role in the seasonal energy balance. We use a simplified coupled (atmosphere-ocean) energy balance model to understand the seasonal amplitude of the various extratropical energy fluxes. The model is found to reproduce the sensitivity of the energy fluxes to the ocean mixed layer depth found in an ensemble of aquaplanet general circulation model simulation with varying mixed layer depths.

Land-ocean contrasts also have a large impact on the seasonal energetics of the extratropical climate system. Over the ocean, zonal heat transport from the land domain is maximized during the summer, and the sum of the insolation and zonal heat transport anomalies is balanced by ocean heat storage. In contrast, over the land, the primary summertime balance is excess solar insolation balanced by an enhanced zonal heat export. The observed seasonal cycle of energy fluxes and the land and ocean temperatures are replicated in a simplified energy balance model that includes land-ocean contrast and the hemispheric differences in fractional land area. The sensitivity of the seasonal cycle in climate (atmosphere and ocean temperatures) – and in the gross partitioning of the mix of energy flux processes that determine the climate – to the fractional land area is further explored in an ensemble of energy balance model integrations. In both the aquaplanet and land-ocean contrast energy balance models, the partitioning of energy fluxes amongst different physical processes can be understood in terms of the sensitivity of those processes to temperature perturbations.