Chapter

INTRODUCTION

The global scale energy fluxes within the climate system are a consequence of both radiative and dynamical processes and their mutual interactions. For example, the annual mean meridional heat transport in the atmosphere and ocean can be diagnosed from the radiative fields – as the net radiative cooling integrated over the polar cap– or from the dynamic fields – as the column integral of the moist static energy flux. The two calculations of the meridional heat transport rely on very different pieces of information but are self consistent with each other; the large scale radiative fields are set up by the dynamic flux of moist static energy and the flux of moist static is influenced by the gradient in the radiative fields. Thus, the diagnostic tool (either the radiative or dynamic fields) used to calculate the meridional heat transport does not prove causality and a complete understanding of the physical processes that determine the magnitude of the heat flux requires that the radiative and dynamic energy fluxes be viewed in a common framework.

In this thesis, we explore the radiative and dynamic controls of large scale energy fluxes from the perspective of the atmospheric energy budget on hierarchy of spatio-temporal scales. We consider the following energy fluxes: (i) absorbed shortwave radiation (ASR), (ii) outgoing longwave radiation (OLR) , (iii) meridional heat transport (MHT), (iv) storage (in the atmospheric or oceanic column), and (v) zonal atmospheric heat transport between the ocean and land domain (ZHT). We adopt a multi-scale approach because spatio-temporal averaging isolates certain physical processes by eliminating other processes. For example, global averaging eliminates the meridional heat transport (since energy can only be reorganzied within the system but not added to or removed from the system by atmospheric and oceanic energy transports) and annual averaging in a steady state system eliminates energy storage. Table 1.1 summarizes the energy fluxes that contribute to the climate system's energy budge on different spatio-temporal scales.

Spatio/temporal averaging	ASR	OLR	MHT	Storage	ZHT
Global/Annual	O	O	X	X	X
Zonal/Annual	O	O	O	X	X
Global/Seasonal	O	O	X	O	X
Zonal/Seasonal	O	O	O	O	X
Land-Ocean contrast/Seasonal	O	O	O	O	O

Table 1.1: Summary of the energy fluxes that contribute to the climate system's energy budget on different spatio-temporal scales. O's (X's) indicate that the energy flux does (does not) contribute.

The analysis of the large scale energy fluxes within the climate system on multiple scales allows us to isolate and understand a small number of processes on large spatio-temporal scales, apply this understanding to smaller spatio-temporal scales, and ultimately put radiative and dynamic energy fluxes into a common conceptual framework. The processes that control the global and annual average energy budget also affect the local and seasonal energy budget with the added complication that dynamic energy transports and energy storage also come into play on the smaller spatio-temporal scales. If we take the lessons we learn from the global and annual average energy budget and apply them to the smaller scale, we can reconcile the relative importance of the dynamic and radiative fluxes on the local and seasonal scale. In this thesis, we start from the largest spatio-temporal scale (the global and annual mean) where a limited number of energy fluxes are isolated and work towards smaller scales (the seasonal cycle and land-ocean contrast) where more physical processes are involved.

In the annual and global average, the climate system achieves radiative equilibrium at the top of the atmosphere (TOA); the annual and global average ASR must equal the annual and global average OLR in a steady climate system. In chapter 2, we ask, what controls the global and annual average net shortwave radiation at the TOA (ASR)? More specifically, the fraction of incident radiation at the TOA that is reflected back to space, the Earth's planetary albedo, is a consequence of both atmospheric reflection and surface reflection. We partition the planetary albedo between atmospheric and surface reflection and demonstrate that the vast majority of the observed annual and global average planetary albedo is due to atmospheric reflection, primarily due to clouds. We also demonstrate that the global and annual average planetary albedo (and thus ASR) in climate models is primarily a consequence of cloud reflection and differences in cloud reflection account for the vast majority of the planetary albedo differences between models and the anticipated changes due to anthropogenic greenhouse gases.

On the equator-to-pole scale, the climate system achieves an annual average three-way energy balance between ASR, OLR, and MHT. For example, the extratropics receive a deficit of ASR (relative to the global average) that is balanced by the sum of the OLR deficit over the same region and MHT from the tropics to the extratropics. In Chapter 3, we demonstrate that the models used in the IPCC's fourth assessment (International Panel on Climate Change [Solomon et al. (2007)) feature a remarkably large spread in the magnitude of MHT. We further demonstrate that this spread is due to inter-model differences in the meridional gradient of ASR and is unrelated to inter-model differences in OLR. The model differences in the meridional gradient in ASR, in turn, are a consequence of model differences in cloud reflection. Thus, the same processes that were found to control the annual and global average ASR in Chapter 2, also influence the equator-to-pole contrast of ASR and thus the dynamic heat transport in the system (MHT). Our results demonstrate that the extratropical deficit of ASR is a consequence of the modeled cloud field and is balanced primarily by MHT and secondarily by OLR suggesting that, on the equator-to-pole scale, MHT is a more efficient pathway toward achieving energy balance than OLR.

We gain further insight into the radiative and dynamic controls of atmospheric energy fluxes by analyzing the seasonal cycle of the observed energy fluxes (Chapter 4). A simplified linearized energy balance model that divides the globe into three boxes (the extratropics in each hemisphere and the tropics) each with an atmosphere and ocean is introduced. The simplified model reproduces the observed mix of energy fluxes over the multitude of spatio-temporal scales considered in this study (ranging from the global annual average to the seasonal land-ocean contrast). The magnitude of the various energy fluxes and storage can be understood in terms of the energy export efficiencies in the model which are defined as the change in the energy flux per unit change in temperature. In this framework, energy fluxes in the climate system are imposed by the spatio-temporal pattern of ASR and the climate system achieves equilibrium via the most efficient energy export and storage pathways. This conclusions persist over the multitude of spatio-temporal scales considered in this study subject only the modification of the number energy fluxes that contribute at each scale (Table 1.1).

Finally, in Chapter 5, we discuss how the conclusions reached in each section relate to each other. Specifically, we argue that the inter-model spread in *MHT* (Chapter 3) is a natural consequence of the inter-model spread in planetary albedo (Chapter 2) and the relative efficiencies of dynamic and radiative energy export on the equator-to-pole scale (Chapter 4).

BIBLIOGRAPHY

International Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. Averyt, M.Tignor, and H. M. (eds.)], 2007: *The scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.