CHAPTER 1 INTRODUCTION

1.1 Rationale / Problem Statement

Around 620 million population lives in Southeast Asian region (Riel, 2012). Their agricultural and industrial productivity are heavily dependent on the climate. Southeast Asia is a tropical area, the weather hovers around the 30°C mark throughout the year, humidity is high and it rains often (Wikitravel, 2013). Climate change may bring destruction to the region. It is therefore important to predict the climate to help communities to better prepare for such destruction, and also to better utilize the benefits that phenomena may bring. Nevertheless, climate becomes more difficult to predict when forces beyond the normal range of variability alter the characteristic physical responses of the climate system itself. This type of situation is essentially what climate scientists now face, in light of the significant increase in carbon dioxide and other greenhouse gases in the atmosphere contributed by industrial growth and associated fossil fuel burning over the past century (Chandler et al., 2006). In spite of the climate model are able to predict over long time intervals but, has not been exploited yet on actual observations to measure the predictability.

Wolf et al. (1985) describe that Lyapunov exponent (LE) is one of the most widely used qualitative measures of complexity in continuous dynamical systems and has verified to be the most useful dynamical diagnostic for chaotic systems. Predictability measurements based on LE for dynamical systems are measured in term of the average exponential divergence or convergence rates of nearby trajectories in phase space. Mikael el al. (2007) show how the stability of a stochastic dynamic system is measured using LE. Many predictability measurements are based on LE such as the maximum Lyapunov exponents (MLE), the finite size Lyapunov exponent (FSLE), the finite time Lyapunov exponents (FTLE) and the largest Lyapunov exponents (LaLE). They can be obtained by generalizing of LE.

The concentration of carbon dioxide in the Earth's atmosphere is of interest due to its impact on the greenhouse effect. Although it is widely accepted that predictability varies with the atmospheric flow, the issue of finding a single best measure to quantify this variation has not yet been settled (Gyarmati et al., 2002).

1.2 Regional Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature has increased 0.76°C over the past 150 years (Intergovernmental Panel on Climate Change, 2007). This global warming has caused greater climatic volatility, such as changed precipitation patterns and increased frequency and intensity of extreme weather events including typhoons, heavy rainfall and flooding, and droughts; and has led to a rise in mean global sea levels. It is widely believed that climate change is largely a result of anthropogenic greenhouse gas (GHG) emissions and, if no action is taken, likely to intensify.

Climate change in Southeast Asia is one of the most significant development challenges confronting Southeast Asia in the 21st century (Intergovernmental Panel on Climate Change, 2007). The climate of Tropical Asia is dominated by the two monsoons: The summer southwest monsoon influences the climate of the region from May to September, and the winter northeast monsoon controls the climate from November to

February. The monsoons bring most of the region's precipitation and are the most critical climatic factor in the provision of drinking water and water for rain-fed and irrigated agriculture.

As a result of the seasonal shifts in weather, a large part of tropical Asia is exposed to annual floods and droughts. The average annual flood covers vast areas throughout the region in India and Bangladesh alone, floods cover 7.7 million ha and 3.1 million ha, respectively (Mirza and Dixit, 1997). At least four types of floods are common: riverine flood, flash flood, glacial lake outburst flood, and breached landslide-dam flood. The latter two are limited to mountainous regions of Nepal, Bhutan, Papua New Guinea, and Indonesia. Flash floods are common in the foothills, mountain borderlands, and steep coastal catchments riverine floods occur along the courses of the major rivers, broad river valleys, and alluvial plains throughout the region.

1.3 Global Climate Models

The Global Climate Models (GCMs) are used extensively in the effort to predict climate changes, such as the effects of increasing greenhouse gases. They are computer programs that simulate the Earth’s climate system in three-dimensions. The climate model used by the Educational Global Climate Model (EdGCM) software was developed at NASA’s Goddard Institute for Space Studies (NASA\GISS). This type of three-dimensional computer model is known as a grid-point GCM.

The principal components of the atmospheric portion of EdGCM are those that express the atmospheric dynamics and the interactions of the Sun’s radiation with the planet while the dynamics calculations help in determining the general circulation of the atmosphere as well as smaller-scale eddy circulations. The radiation calculations define the energy balance of the Earth by mean of evaluating the reflection and absorption of solar radiation through the surface and atmosphere, and through the remittance of thermal energy back to space. Moreover, the radiation calculations in a GCM must take into account cloud thickness and cloud distribution, surface conditions, and all significant greenhouse gases and aerosols (Chandler et al., 2006).

Determining simple versus complex climate models is not necessarily straightforward if climate models of varying complexity exist. This is due to climate models may be considered more complex if they incorporate additional dimensions, increase the spatial or temporal resolution at which calculations are applied, represent the physics more completely, or incorporate parameterizations that describe additional components of the climate system (e.g. oceans, vegetation, ground hydrology, ice sheets, the carbon cycle, etc.) as shown in Figure 1. Possibly the most important of these “additions” to the atmospheric model are the coupling of the atmospheric GCMs to three-dimension ocean circulation models (Chandler et al., 2006).

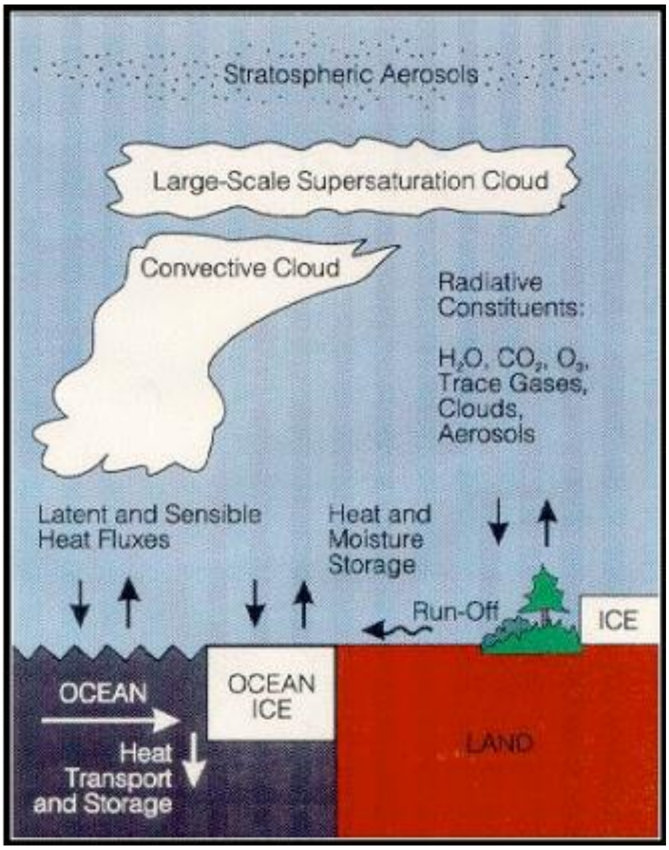

Figure 1.1 Schematic of the physical components of the climate system (Chandler et al., 2006).

1.4 Literature Review

Yoden and Nomura (1993) discuss an application of the finite-time Lyapunov exponent (FTLE) and vector to the atmospheric predictability problem. The results show that FTLE which is the growth rate of small perturbations depends upon the reference solution as well as the prescribed time interval. Moreover, the finite-time Lyapunov vector corresponds to the largest Lyapunov exponents which gives the stream function field of the fastest growing perturbation for the time interval. These quantities of FTLE might be used as a measure of the time dependent predictability in operational numerical weather prediction (NWP).

Eckhardt and Yao (1993) define FTLE and discuss its computational aspects. FTLE is the projection of the linearization of the flow at the point onto the expanding direction. The derivative is computed locally but the expanding direction contains correlations along the trajectory. FTLE is useful in predictions and control of chaos.

Boffeta et al. (1998) investigate the predictability problem for the different characteristic timescales systems. The method is first illustrated on a simple numerical model obtained by coupling two Lorenz systems. They adopt a generalization of the Lyapunov exponent based on the natural concept of error growing time at fixed error size. The predictability time defined in terms of the finite size Lyapunov exponent displays a strong dependence on the error magnitude. It is shown that the finite size Lyapunov exponent (FSLE) is more suitable for characterizing the predictability of complex systems, in which the growth rate of large errors is not ruled by the Lyapunov exponent.

Basu et al. (2002) study atmospheric predictability based on the Lyapunov exponent (LE). They employ FSLE analysis to assess predictability of atmospheric boundary layer flows as a function of scale. The results show that predictability strongly depends on the scale at which the process is considered with larger predictability at larger scales.

Guillaume (2002) discusses about application of Lyapunov theory in chaotic systems to the dynamics of tracer gradients in two-dimensional flows. His driving force is to tighten the link between alignment properties of tracer gradients in two dimensional aperiodic flows and Lyapunov theory because of two-dimensional turbulence represents the most challenging test case for mixing and stirring ideas. He uses such simulations to examine FTLE and vectors. The highlight of this study is the different properties associated with finite time Lyapunov vectors and exponents such as convergence in time and alignment properties. The relations between the different categories of Lyapunov vectors and the spatial distribution of FTLE are discussed as well. The results show that the distribution of FTLE shows the intricacy of chaotic mixing in two dimensions.

Liu et al. (2004) investigate the chaotic characteristics and maximum predictable time scale of the observation series of hourly water consumption the largest Lyapunov exponent. A chaotic system is mainly identified by testing Lyapunov exponents, evaluating fractal dimensions, and analyzing Kolmogorov power spectra. The largest Lyapunov exponents of water consumption series with one-hour and 24-hour intervals are calculated respectively. The results show that chaotic characteristics obviously exist in the hourly water consumption system; and that observation series with 24-hour interval have longer maximum predictable scale than hourly series.

Francesco et al. (2004) characterize mixing strength at the mesoscale in different areas of the Mediterranean Sea using FSLE. FSLE has been introduced in order to study non-asymptotic dispersion processes, which is particularly appropriate to analyze transport in closed areas. The results indicate that FSLE provides a direct method for computing simultaneously the mixing activity for control transport at a given scale.

Ding and Li (2007) present a definition of nonlinear FTLE for chaotic systems. The results show that with the nonlinear FTLE and its derivatives, the limit of dynamic predictability in large classes of chaotic systems can be efficiently and quantitatively determined.

Sangapate and Sukawat (2007) investigate predictability of a spectral shallow water model by using LE, MLE and FSLE on two standard test cases. Results from the experiments show that, the predictability time of the spectral shallow water model is related to LE and depend on model resolution and angular velocity. In the case of high resolution and low angular velocity, the maximum predictability time scale of the spectral shallow water model is longer than that of the low resolution and high angular velocity.

Ould et al. (2007) present the expected variability predictability in the problem of load curves for the Tunisian Company of Electricity and Gas. The objective of this study is to investigate the maximum prediction of the daily peak load time series by using the largest Lyapunov exponent estimation. The result shows the limits of the models of medium-term forecast because of the presence of chaos, which leads to unpredictability.

Guégany and Leroux (2008) propose a novel methodology for forecasting chaotic systems which is based on exploiting the information conveyed by the local Lyapunov exponent (LLE) of a system. They show how the methodology can improve forecasting within the attractor and illustrate the results on the Lorenz system.

Ismael et al. (2010) analyze the sensibility of FSLE, which is a local measure of particles dispersion. Although mathematically appealing, it is rather unclear how robust are FSLE analyses when confronted to real data, in other words, data affected by noise and with limited scale sampling.

Saiuparad and Sukawat (2012) present a new predictability measurement, Supremum Lyapunov Exponent (SLE) which is based on LE. SLE is applied to 2 cases of the Asian northeast monsoon forecast under a global warming scenario by a shallow water model. The results show that the forecasts from slightly difference initial conditions converge after 3-day forecasts. That is, the shallow water model is not suitable for the purpose of climate downscaling.

Sangapate (2012) performs numerical experiments for a spectral shallow water model and investigate the predictability times of two standard test cases. The purpose is to investigate the measurements of predictability by LE, MLE, FSLE and Lagrangian structure function (LSF). Results from the study indicate that the predictability time is an inverse of the angle between the axis of solid body rotation and the polar axis of the spherical coordinate system and the predictability time is depend on the model resolution. In addition, FSLE gives predictability time similar to LSF while LSF gives longer predictability time than that of MLE.

Vallejo and Sanjuán (2013) use FTLE distributions to derive the shadowing timescales of a given system. They show how to obtain information about the predictability of the orbits even when using arbitrary initial orientation for the initial deviation vectors. The results show that a chaotic system can have poor predictability, understand as having low shadowing times. This predictability is linked to the structural sensitivity of the system and the validity of potential long computer simulations.

Karrasch and Haller (2014) use ridges of FSLE field as indicators of hyperbolic Lagrangian Coherent Structures (LCSs). A rigorous mathematical link between the FSLE and LCSs is missing. They prove that an FSLE ridge satisfying certain conditions does signal a nearby ridge of some FTLE fields, which in turn indicates a hyperbolic LCS under certain conditions. The result shows that being sensitive to initial conditions, chaos is equally sensitivity to appropriate simulation time steps.

From the literature reviews, several predictability measurements are used to measure and to indicate the sensitivity of the models. The predictability measurements as reviewed above are summarized in Table 1.1.

Table 1.1 Summary of literature reviews.

Authors	Year	Measurement of Predictability
Yoden et al.	1993	FTLE
Eckhardt et al.	1993	FTLE
Boffeta et al.	1998	FSLE
Basu et al.	2002	FSLE, MLE
Guillaume et al.	2002	FTLE
Liu et al.	2004	LE
Francesco et al.	2004	FSLE
Ding et al.	2007	FTLE
Sangapate and Sukawat	2007	LE, MLE, FSLE
Ould et al.	2007	MLE
Guégany and Leroux	2008	LLE
Ismael et al.	2010	FSLE
Saiuparad and Sukawat	2012	LE, SLE
Sangapate	2012	LE, MLE, FSLE, LSF
Vallejo and Sanjuán	2013	FTLE
Karrasch and Haller	2014	FSLE, FTLE, LCS

In this research, six methods of predictability measurements e.g., LE, MLE, FSLE, FTLE, LLE and SLE are applied to Southeast Asian climate predictions by the EdGCM.

1.5 Objective

To investigate the predictability of Southeast Asian regional climate change by the Educational Global Climate model using a modified Lyapunov exponent method.