CHAPTER 3 METHODOLOGY

3.1 Single Level Primitive Equation (SILEPE) Model

In this research, the single level primitive equation (SILEPE) model follows Krishnamurti (1986) is used. This model uses the shallow-water equation to represent the atmospheric system,

$$\frac{du}{dt} - fv + g\frac{\partial z}{\partial x} = 0, \tag{3.1}$$

$$\frac{dv}{dt} + fu + g\frac{\partial z}{\partial y} = 0, \tag{3.2}$$

$$\frac{dz}{dt} + z\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0, \tag{3.3}$$

The above three equations may be written as,

$$\frac{du}{dt} = -g\frac{\partial z}{\partial x} + fv, \tag{3.4}$$

$$\frac{dv}{dt} = -g\frac{\partial z}{\partial y} + fu, \tag{3.5}$$

$$\frac{dz}{dt} = -z\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right), \tag{3.6}$$

where u is the x component of the wind vector (m/s).
v is the y component of the wind vector (m/s).
z is the geopotential height (m).
g is the acceleration of gravity (m/s^2).
f is the coriolis force.

The advective terms in the model are treated via a semi-Lagrangian advection scheme while time integration is accomplished through the Matsuno time scheme. The 9-points Lagrange interpolation scheme is used for obtaining the values at the departure points. If F represents the function to be interpolated at the point P, this interpolation scheme is defined as,

$$F(P) = \sum_{\substack{i=I-1 \\ j=J-1}}^{\substack{j=J+1 \\ i=I+1}} W_{i,j} F_{i,j}, \tag{3.7}$$

where $W_{i,j}$ is the weights for the Lagrange interpolation scheme.

In the computation of the forcing functions, the pressure gradient force terms $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial x}$ in the momentum equations and the divergence term $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$ in the continuity equation are approximated through the standard centered differencing. The sequence to run the model is shown in Figure 3.1. The prediction equations used here has the zonal and meridional components of the wind field (u and v) and the height (z) field as their predicted variables.

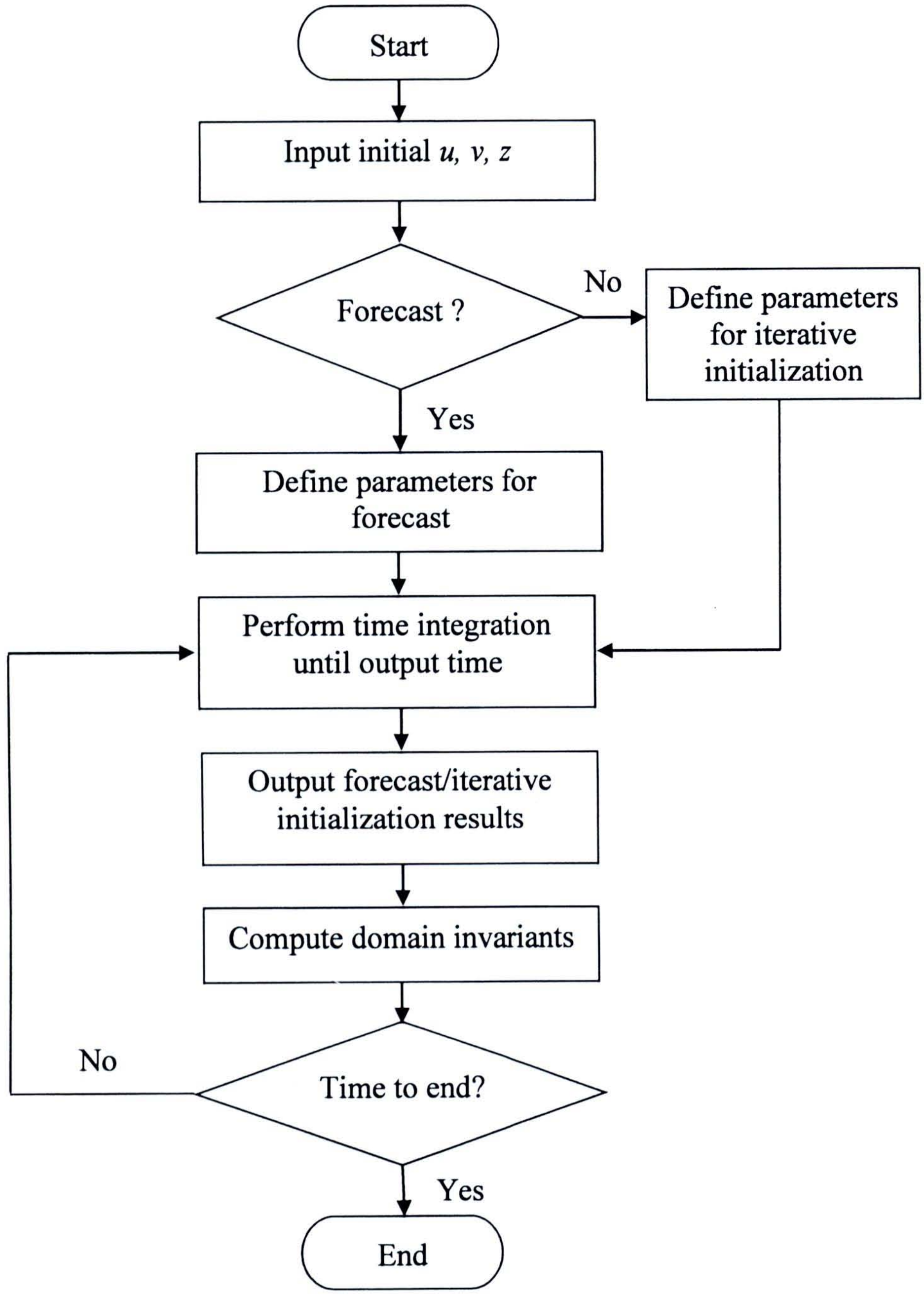


Figure 3.1 Flow chart showing sequence of running in SILEPE model (Krishnamurti, 1986).

3.2 The Data

3.2.1 The Data for Testing the Model

The first stage in this research is to test the single level primitive equation (SILEPE) model that is used in this study. The summary of cases for the experiments of testing the model (Wongsaming, 2008) is shown in Table 3.1.

Table 3.1 Summary of cases for testing the model.

Case of Cold Surge Reaching Thailand	Case
9 Dec 2002	A. One day before the event B. Two days before the event
15 Dec 2005	C. One day before the event D. Two days before the event

The data for the above cases are derived from NCEP/NCAR reanalysis (NOAA National Center for Environmental Prediction, 1996) of 1 degree grid resolution (about 100 km) and there are data for every 6 hr, with 17 pressure levels. These data are used for testing the forecast performance of the SILEPE. Each case consists of two experiments: experiment 1, run SILEPE 1 day before the cold surge event and experiment 2, run SILEPE 2 days before the cold surge event.

3.2.2 The Data for Breeding Method

Since the objective of this research is to study patterns of cold surge over Southeast Asia under the influence of global warming in which NCEP/NCAR data reanalysis do not have data at the 500 hPa for global warming simulations. Therefore the data obtained from the Bjerknes Centre for Climate Research (BCCR) at University of Bergen, Norway under the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset for preparing the Fourth Asssessment Report (AR4) of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change - IPCC, 2009) are selected for testing the generation of initial perturbation in the breeding process.

The Special Report on Emissions Scenario (SRES) data and Non-SRES for the Atmospheric Environment are shown in Table 3.2 (NOAA National Center for Environmental Prediction, 1996). These scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The scenarios encompass different future developments that might influence greenhouse gas (GHG) sources and sinks, such as alternative structures of energy systems and land-use changes.

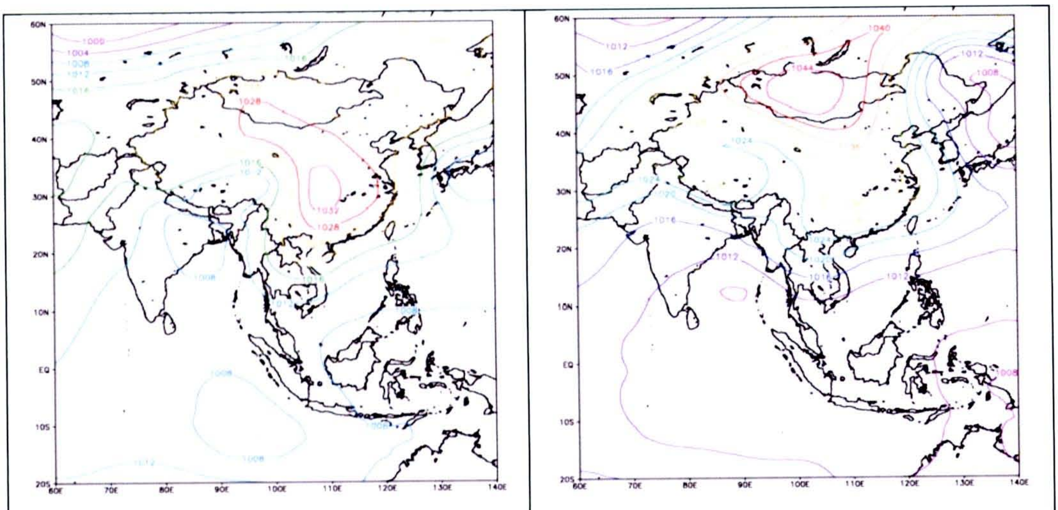
Table 3.2 The Special Report on Emissions Scenario (SRES) data and Non-SRES for the Atmospheric Environment (NOAA National Center for Environmental Prediction, 1996).

SRES	Key Assumptions
A1B	A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.
B1	A convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource-efficient technologies.
A2	A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.
B2	A world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.
Non-SRES	**Key Assumptions**
PICTL	Experiments run with constant pre-industrial levels of greenhouse gasses.
20C3M	Experiments run with greenhouse gasses increasing as observed through the 20th century.
COMMIT	An idealised scenario in which the atmospheric burdens of long-lived greenhouse gasses are held fixed at AD2000 levels.
1PTO2X (1% to double)	Experiments run with greenhouse gasses increasing from pre-industrial levels at a rate of 1% per year until the concentration has doubled and held constant thereafter.
1PTO4X (1% to quadruple)	Experiments run with greenhouse gasses increasing from pre-industrial levels at a rate of 1% per year until the concentration has quadrupled and held constant thereafter.

This data set has the grid resolution about 2.8×1.38 degree and collected to yearly tar file which contain several daily NetCDF files.

3.3 Breeding Case Selection

The surface pressure from WCRP CMIP3 multi-model database are plotted to inspect the cold surge. For example, the A2 run at 12Z 07 DEC 2059 clearly shows a strong cold surge entering Southeast Asia (Figure 3.2a). The corresponding breeding case from COMMIT is shown in Figure 3.2b.



a) A2 b) COMMIT

Figure 3.2 The breeding case of 12Z 07 DEC 2059 from a) A2 and b) COMMIT.

Wind and geopotential height at 500 hPa of A2 and COMMIT used for testing the generation of initial perturbations in breeding process are shown in Table 3.3.

Table 3.3 Experiment cases for testing the generation of initial perturbations in breeding process.

Model Domain	lat: 40°S to 80°N, long: 180°W to 180°E
Model Resolution	$\Delta x = \Delta y = 1^\circ$, $\Delta t = 60\ s$.
Initial Condition	IPCC data, 500 hPa Case 1 12Z 08 DEC 2049 Case 2 12Z 02 DEC 2056 Case 3 12Z 20 DEC 2058 Case 4 12Z 07 DEC 2059 Case 5 12Z 20 DEC 2062
Boundary Condition	Cyclic in the west-east boundary Open in the north-south boundary
Forecast Time	4 days
Breeding Cycle (Rescaling Time)	Every 12 hours

The above cases are selected from the events that surface pressure of 1012 hPa and 1020 hPa enter Thailand.

The downloaded variables are geopotential height (zg), zonal wind component (ua) and meridional wind component (va). Examples of the downloaded files are shown in Table 3.4.

Table 3.4 Examples of data for the experiments.

For	**File Name**
Control Run	pcmdi.ipcc4.bccr_bcm2_0.sresa2.run1.daily.ua_A2_2056-2065.nc pcmdi.ipcc4.bccr_bcm2_0.sresa2.run1.daily.va_A2_2056-2065.nc pcmdi.ipcc4.bccr_bcm2_0.sresa2.run1.daily.zg_A2_2056-2065.nc
Initial Perturbation	pcmdi.ipcc4.bccr_bcm2_0.commit.run1.daily.ua_A2_2056-2065.nc pcmdi.ipcc4.bccr_bcm2_0.commit.run1.daily.va_A2_2056-2065.nc pcmdi.ipcc4.bccr_bcm2_0.commit.run1.daily.zg_A2_2056-2065.nc

The meaning of file name is, for example

pcmdi.ipcc4.bccr_bcm2_0.sresa2.run1.daily.ua_A2_2056-2065.nc

Is Part Of : pcmdi.ipcc4

Center Acronym : bccr

Model Name : bcm2.0

Special Report on Emissions Scenario : sresa 2

Run Time : run 1

Run Result : daily

Variable Name : ua

Scenario : A2

Collect Years : 2056 – 2065

File Type : .nc or NetCDF

The steps for preparing the data set from the WCRP CMIP3 multi-model database are shown in Figure 3.3.

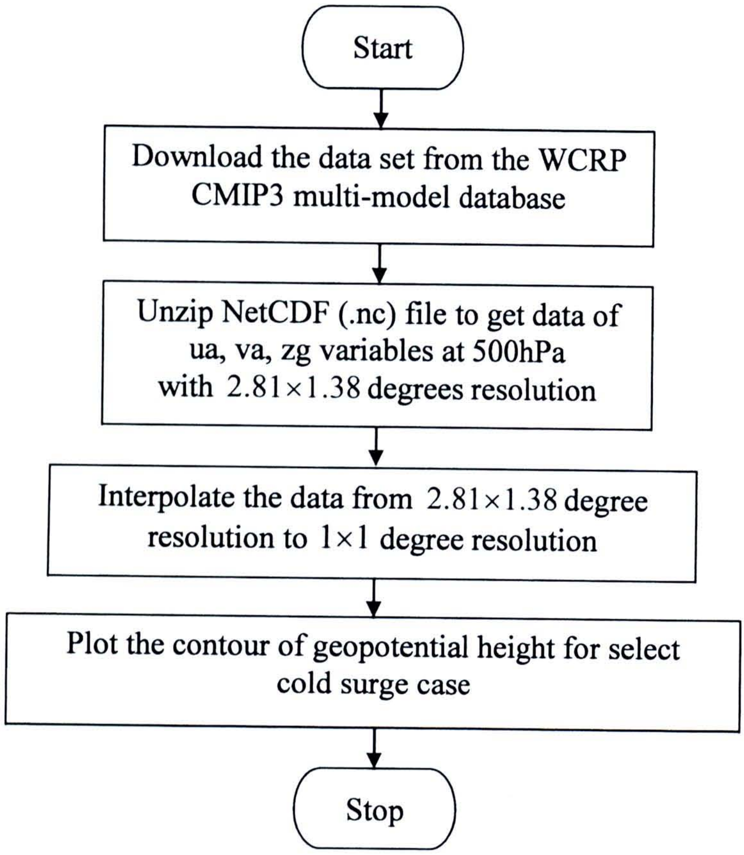


Figure 3.3 The steps for preparing the data set from the WCRP CMIP3 multi-model database.

3.4 Domain

3.4.1 Study Domain

The domain of study covers 60°E to 140°E and 20°S to 60°N (Figure 3.4).

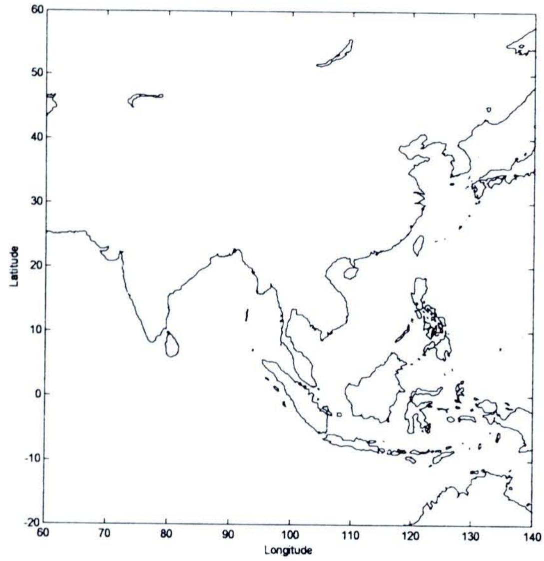


Figure 3.4 The domain of study.

3.4.2 Experiment Domain

The domain used for running the model covers 180°W to 180°E and 40°S to 80°N in order to have the east-west cyclic boundary and to reduce the problem at the north and south boundaries (Figure 3.5).

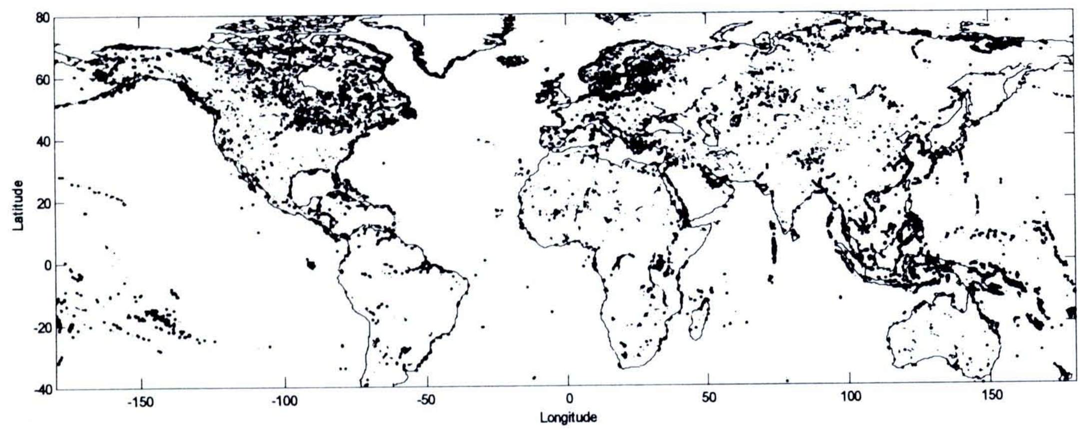


Figure 3.5 The domain of experiments.

3.5 Breeding Method for Generation of Initial Perturbation

Breeding method was developed by Toth and Kalnay (1993) as a method to generate initial perturbations or "breeding of fast-growing modes'' for short-to-medium-range atmospheric ensemble forecasts at the National Centers for Environmental Prediction (NCEP). The initial perturbation obtained by breeding are known as bred vectors, and they are essentially the finite-time, nonlinear extension. In the following steps the procedure to compute bred vectors in mathematical terms is described.

1) Perform a control run (CTL) from the nonlinear model

$$f(x,t+\Delta t)=M[f(x,t)], \tag{3.8}$$

where $f(x,t)$ is a function vector.

t is time.

Δt is time step size.

M is a map that has at least a bounded gradient.

Assume $f=f(x,t)$ as evolving basic solution that satisfies Equation (3.8) with a given discretization in space and time integration scheme.

2) Find the initial value $\widetilde{Z}(x_i,0)$ for generation of initial perturbation $\delta Z(x_i,0)$ from the difference in geopotential height between A2 scenario and COMMIT non-scenario over Southeast Asia region (81×81 grid points) then perform initialization of this results using SILEPE in order to balance geopotential height and wind field.

$$\widetilde{Z}(x_i,0) = Z(x_i,0)_{A2} + [Z(x_i,0)_{A2} - Z(x_i,0)_{COMMIT}];\ i = 1,2,....,81\times 81 \quad (3.9)$$

3) Find the initial perturbation. For an initial state ($t=0$), find the difference of geopotential height between $\widetilde{Z}(x_i,0)$ and A2 scenario over Southeast Asia region, which is the initial perturbation of geopotential height $\delta Z(x_i,0)$,

$$\delta Z(x_i,0) = \widetilde{Z}_i(x_i,0) - Z(x_i,0)_{A2};\ i = 1,2,....,81\times 81 \quad (3.10)$$

4) Find the Euclidean norm of this initial perturbation. The Euclidean norm is denoted $\|\delta Z(x_i,0)\|$ and gives the length of n-vectors $\delta Z(x_i,t) = \delta Z_i = (\delta Z_1, \delta Z_2, ..., \delta Z_n);\ \ n = 81\times 81$. It can be computed as

$$\|\delta Z(x_i,t)\| = \sqrt{\delta Z_1^2 + \delta Z_2^2 + ... + \delta Z_n^2}$$

5) Perform the perturbation run. Add the initial perturbation to the basic solution of geopotential height, integrate the perturbed initial condition with SILEPE forward for $\delta t = 12$ hr, and subtract the original unperturbed solution CTL (obtained from using A2 scenario as the initial condition) from the perturbed nonlinear integration (perturbation run (PRT)) with $\delta t = 12$ hr.

$$\overline{\delta Z(x_i,t+\delta t)} = [M[Z(x_i,t+\delta t)] + \delta Z(x_i,t+\delta t)]_{PRT} - M[Z(x_i,t+\delta t)]_{CTL}] \quad (3.11)$$

6) Find the Euclidean norm of Equation (3.11), denoted $\left\|\overline{\delta Z(x_i,t+\delta t)}\right\|$

7) Use rescaling rule to adjust the norm of the initial perturbation to the initial norm for every δt hr.

$$\left\|\overline{\delta Z(x_i,0)}\right\| = R(x_i,t+\delta t)\left\|\overline{\delta Z(x_i,t+\delta t)}\right\| \quad (3.12)$$

Equivalently, the rescaling factor is,

$$R(x_i, t+\delta t) = \frac{\left\| \overline{\delta Z(x_i, 0)} \right\|}{\left\| \overline{\delta Z(x_i, t+\delta t)} \right\|} \tag{3.13}$$

8) Generate the new initial perturbation by,

$$\delta Z(x_i, t+\delta t) = R(x_i, t+\delta t)\overline{\delta Z(x_i, t+\delta t)} \tag{3.14}$$

This rescaled initial perturbation is called bred vector.

Note that, the loop from step 2) to step 6) is called "breeding cycle".

9) Steps 5) to 8) are repeated for the next time interval and so on until 14-day forecast is done. The generated bred vector will have 50 values.

The above processes can be shown as flowchart in Figure 3.6.

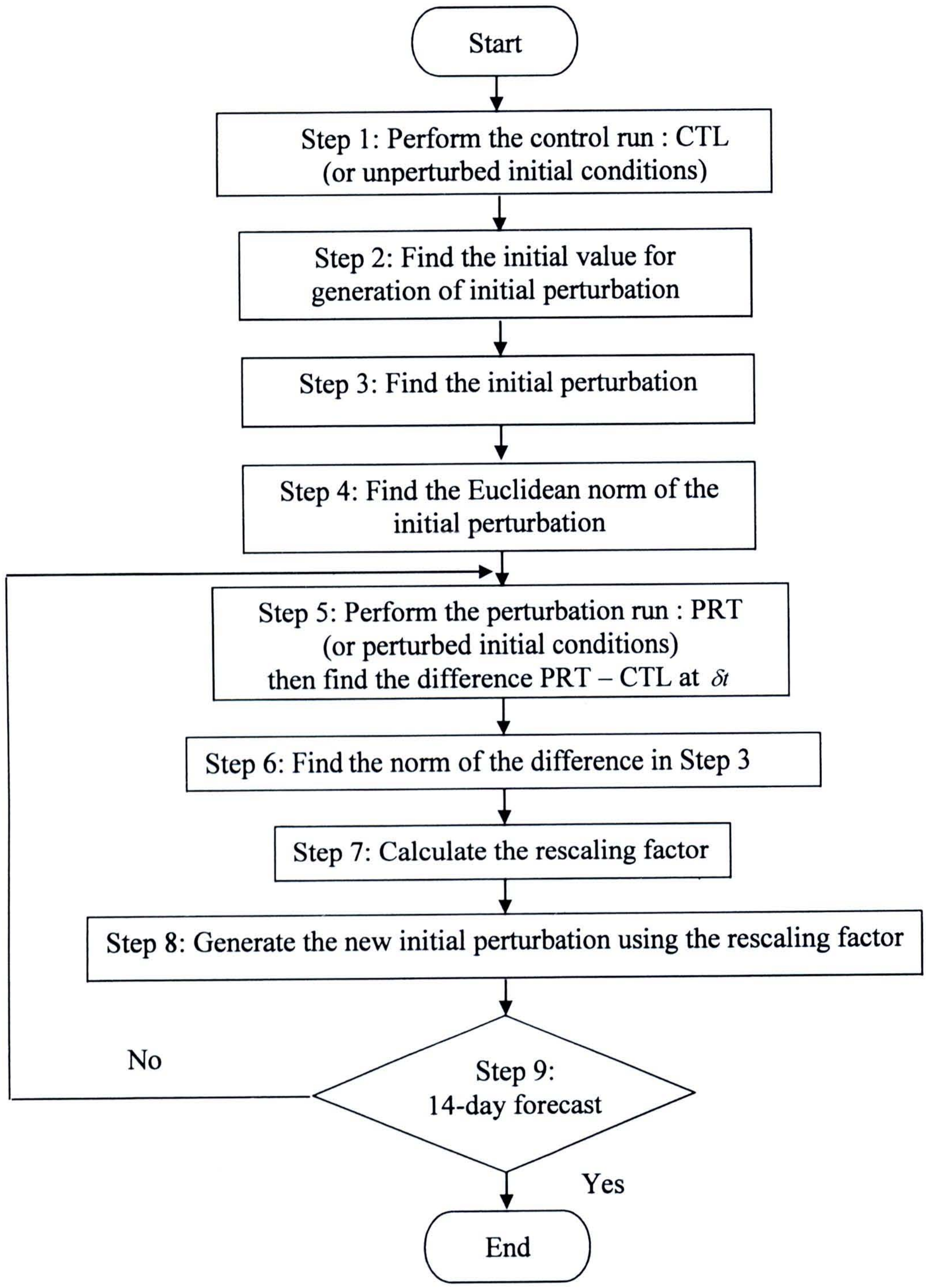


Figure 3.6 Flow chart showing the steps of breeding method.

3.6 Ensemble Forecasting from Bred Vector

After obtaining the bred vectors from the breeding method, the initial condition from A2 scenario is perturbed by adding and subtracting bred vectors over the study domain. The SILEPE is run for 4-day forecast to generate 50 ensemble members.