Controlling the global weather

Ross N. Hoffman, Mark Leidner,
and John Henderson

Atmospheric and Environmental Research, Inc.
131 Hartwell Avenue, Lexington, MA 02421 USA

Overview

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- Current applicable NWP practice
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Motivation

- **Imagine: no droughts; no tornadoes; no snow storms during rush hour; etc.**
- **Not to eliminate hurricanes, but to control the paths of hurricanes.**

  To essentially forbid hurricanes from striking population centers.

- **Not to change the climate, but to control the precise timing and paths of weather systems.**

Introduction

- We present the underlying concepts for our approach
- Outline the system architecture of a controller for the global atmosphere
- Describe the components of such a controller.
- Legal and ethical questions, and the issues of feasibility and cost/benefit trade-offs are only briefly considered.
- The existence of the technology to implement the weather controller is plausible at the time range of 30–50 years.

Theoretical basis

- **The earth's atmosphere has been hypothesized to be chaotic.**
- **Chaos implies that there is a finite predictability time limit**

  No matter how well the atmosphere is observed and modeled.

- **Chaos also implies sensitivity to small perturbations.**
- **A series of such perturbations to the atmosphere might be devised to effectively control the evolution of the atmosphere**

  If the atmosphere is observed and modeled sufficiently well.

Predictability limits

- **Motions occur over a huge spectrum of scales in the atmosphere.**
- **Smaller spatial scales have shorter time scales.**

  Errors in the smallest scales will completely contaminate those scales on the characteristic time scale associated with that spatial scale.

- **These errors will then induce errors in the next larger scale and so on. . . .**

- **At the same time, advection implies that tiny errors on the large scales will in turn cause large errors on the shortest scales.**

These interactions lead to a finite predictability time limit.

Control of chaotic systems

A sequence of very small amplitude, but precisely chosen perturbations will steer the chaotic system within its attractor.

- Resonance: one system entrains another with partial information
- Unstable periodic orbits can be followed

Current NWP operational practice

Current operational practice at NWP centers illustrate that the dynamics governing the atmosphere can be extremely sensitive to small changes in initial conditions daily. Examples summarized in what follows include:

- **Data assimilation**
- **Generation of ensembles**
- **Targeted observations**

Control of atmospheric models: Operational examples

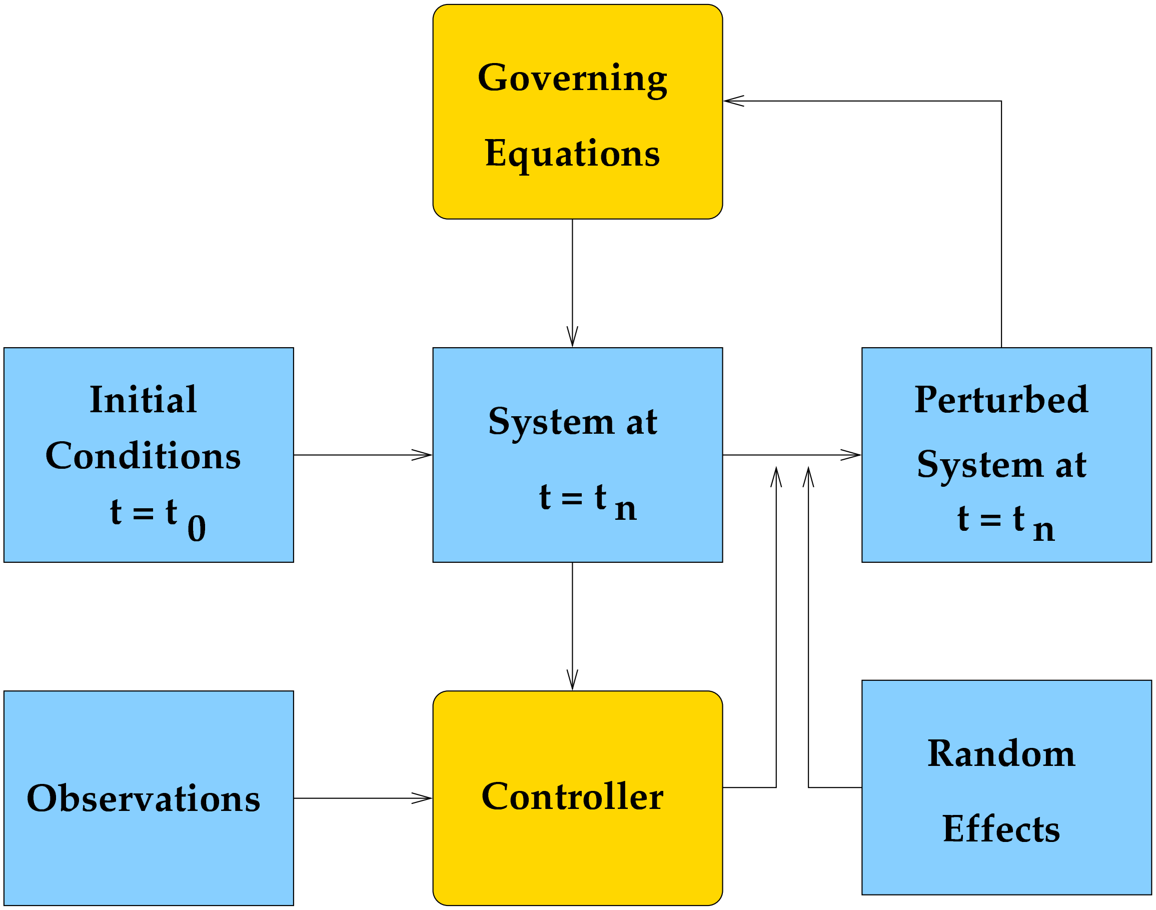
- 4d-VAR data assimilation finds the smallest global perturbation, as measured by the a priori or background error covariances
- Singular vectors, used to generate ensemble forecasts, are the fastest growing perturbations about a given model forecast over a finite time interval
- Targeted observations are deployed in that region of the initial state which, if better observed, would improve the forecast of that storm

System architecture

Our proposed controller is similar in general to feedback control systems common in many industrial processes; however it is greatly complicated by the

- **Number of degrees of freedom required to represent the atmosphere adequately**
- **The nonlinear nature of the governing equations**
- **The paucity of observations of the atmosphere**
- **The requirement that control be effected at significant time lags**
- **The difficulty of effecting control**
- **The ambiguous nature of the figure of merit**

Global weather controller schematic flow chart



Eliminate the “observations” and “controller” to show how a NWP model approximates the atmosphere

The same flow chart describes the data assimilation system (the estimator) within the controller itself

Complicating factors

The number of degrees of freedom required to represent the atmosphere adequately.

The nonlinear nature of the governing equations. The atmosphere is nonlinear and sometimes discontinuous. For example, clouds have sharp edges.

The paucity and inaccuracy of observations of the atmosphere. Satellites provide a huge volume of information. However this information is not always in the right place, accurate enough, or of the right type.

The control must be effected at significant time lags to minimize the size of the perturbations, yet the system is inherently unpredictable at long lead times.

The difficulty of effecting control. The control mechanisms do not yet exist. The ideal perturbations, while small in amplitude, may be large in scale.

The ambiguous nature of the figure of merit. For inhabitants of New Orleans, eliminating a hurricane threat to that city may take precedence over all else. But in general attempting to satisfy multiple objectives may result in conflicts.

System components

- Numerical weather prediction
- Data assimilation systems
- Satellite remote sensing
- Perturbations
- Computer technology
- Systems integration

Numerical weather prediction

- **Advances in computer power will enable the refinement of NWP**

  Current high resolution meso-scale models point the way for advances in global models

- **Extrapolating for 30 years suggests global model resolution of approximately** $250\ m$

- **More and more of the physics of the atmosphere will be resolved explicitly**

Data assimilation systems

- **The current state-of-the-art is 4d-VAR**

  Operational 4d-VAR assumes a perfect model over short time periods (6 hours or 24 hours) and finds the initial condition at the start of the period, which best fits all available observations during the period

- **Current research focuses on approximations to the extended Kalman filter**

  The principal issue is to efficiently describe and evolve the huge covariance matrix describing the uncertainty of the system state.

Satellite remote sensing

- New sensors have very high spectral resolution

  And will produce higher vertical resolution for the retrieved temperature and moisture profiles

- Higher resolution, greater numbers of satellites, and higher accuracy are expected in the future

- Future lidar sensors will provide high resolution, high accuracy observations of winds and atmospheric composition

Perturbations

- **Aircraft contrails**

  Contrails are essentially cirrus clouds and influence both the solar and thermal radiation. Slight variations in the timing, levels, and routes of aircraft would produce perturbations.

- **Solar reflectors**

  In low earth orbit, these would produce bright spots on the night side, and shadows on the day side.

- **Space solar power**

  SSP generators downlink energy in the microwave. This may be a tunable atmospheric heat source.

- **Wind power**

  An enormous grid of fans which doubled as wind turbines might transfer atmospheric momentum in the form of electric energy.

Computer technology

The requirements of global weather control are staggering, but global NWP models at the sub-kilometer scale seem attainable in the 30–50 year time frame.

- **Can the pace of advances in computer technology can be maintained?**

Systems integration

The global weather control system is a mega-system. Tools and methodologies for mega-systems engineering have been driven by recent defense and aerospace projects, such as

- **The space shuttle**
- **The strategic defense initiative (SDI)**

Phase 1 objectives

- Develop a method to calculate the perturbations needed to control the track of a hurricane.
- Quantify the size of the perturbations needed to do this.

Phase 1 experimental setup

The basic experiment is simply a variation on 4dVAR:

- **Consider some initial forecast of a hurricane**

  This is the unperturbed run U. From time 0 to T.
  With states $U(0)$ and $U(T)$.

- **Create a goal state $G(T)$ with the hurricane positioned at time T to be 50 km east of the position in $U(T)$**

- **Use 4dVAR to find an optimal perturbed simulation P**

  P simultaneously minimizes the difference from the goal $P(T) - G(T)$ and the initial state $P(0) - U(0)$.

  $P(0) - U(0)$ is the minimal perturbation to get within $P(T) - G(T)$ of the goal.

Phase 1 cost function

For Phase 1 both the goal mismatch and the size of the initial perturbation are measured with a simple quadratic norm:

$$J = \sum_{x,i,j,k,t} \left(\frac{P_{xijk}(t) - U_{xijk}(t)}{S_{xk}} \right)^2$$

Here $x \in \{u, v, \theta\}$, i, j, k range over all the grid points and $t \in \{0, T\}$. The scaling S depends only on variable and level.

Phase 1 case study

- **Hurricane Iniki at 06 UTC 10 September 1992 provides our initial state**
- **The MM5 computation grid is 97×79, with a $40\ km$ grid spacing, and ten layers in the vertical**
- **Simplified parameterizations of the boundary layer, cumulus convection, and radiative transfer are used**
- **The observed sea surface temperature is increased by $5\ K$ everywhere in our simulations**

We found this was enough to maintain the hurricane when using the simplified parameterizations. Only the simplified parameterizations are currently available in the MM5 4d-VAR system.

Phase 1 results

- **Plots of the cost function**

  Cost function vs. iteration

  Cost function profile for winds vs. model layer

  Cost function profile for temperature vs. model layer

- **Model surface (lowest layer) pressure and winds**

  Unperturbed initial conditions

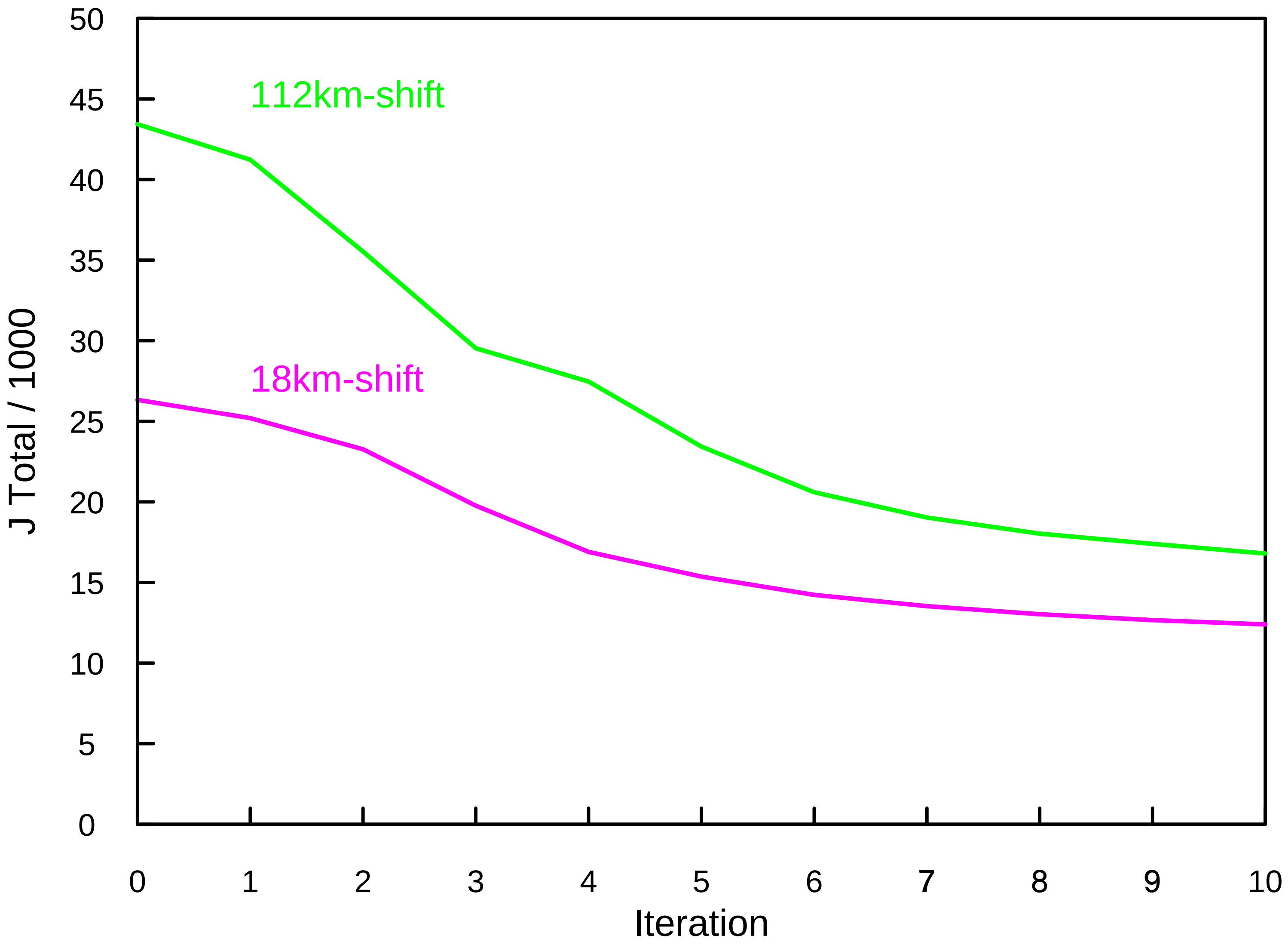
  Unperturbed 6 hour forecast

  Perturbed 6 hour forecast

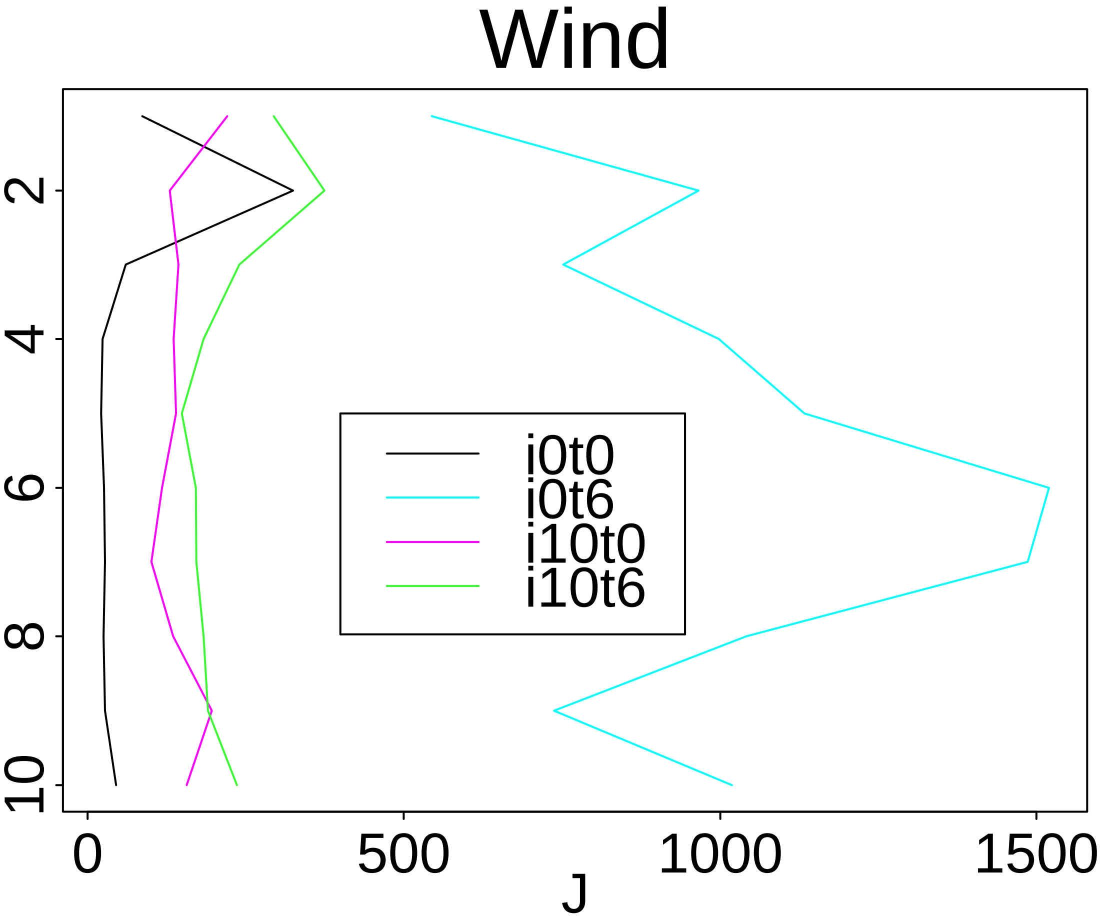
  Perturbed initial conditions

  Perturbation

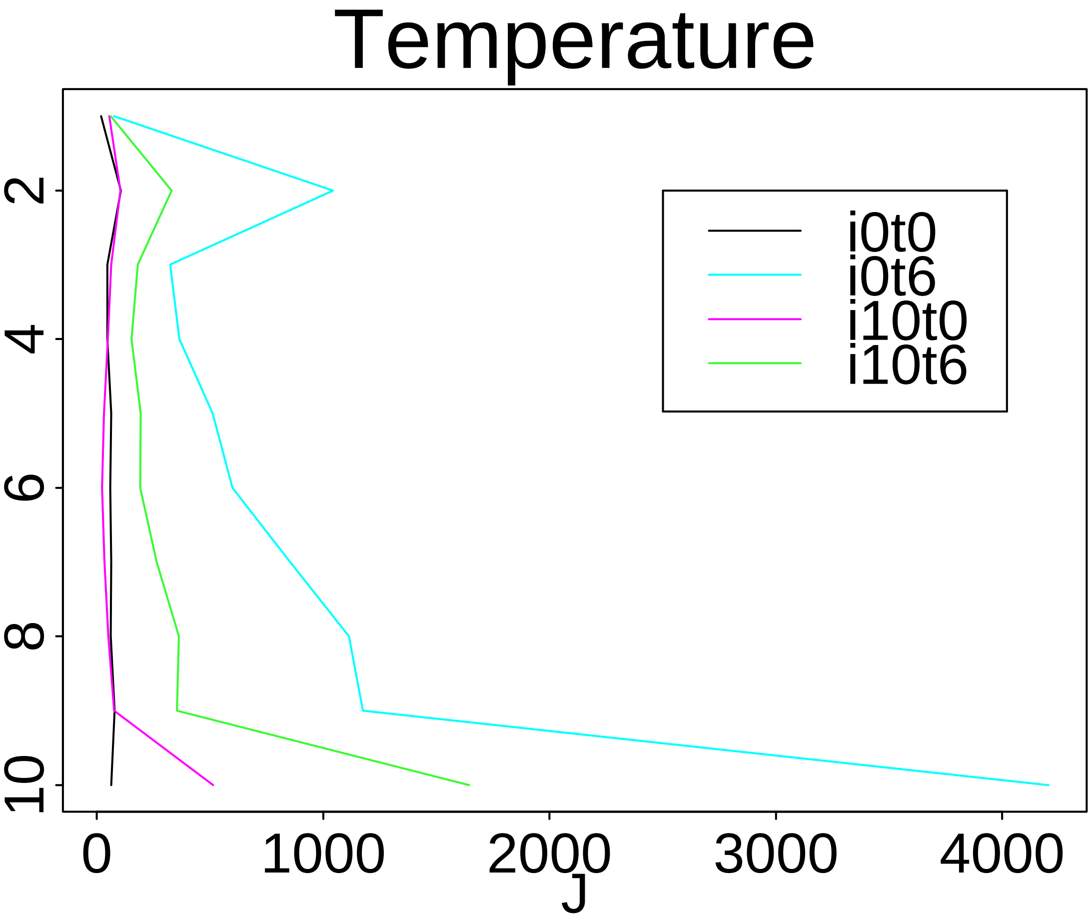
Cost function vs. iteration



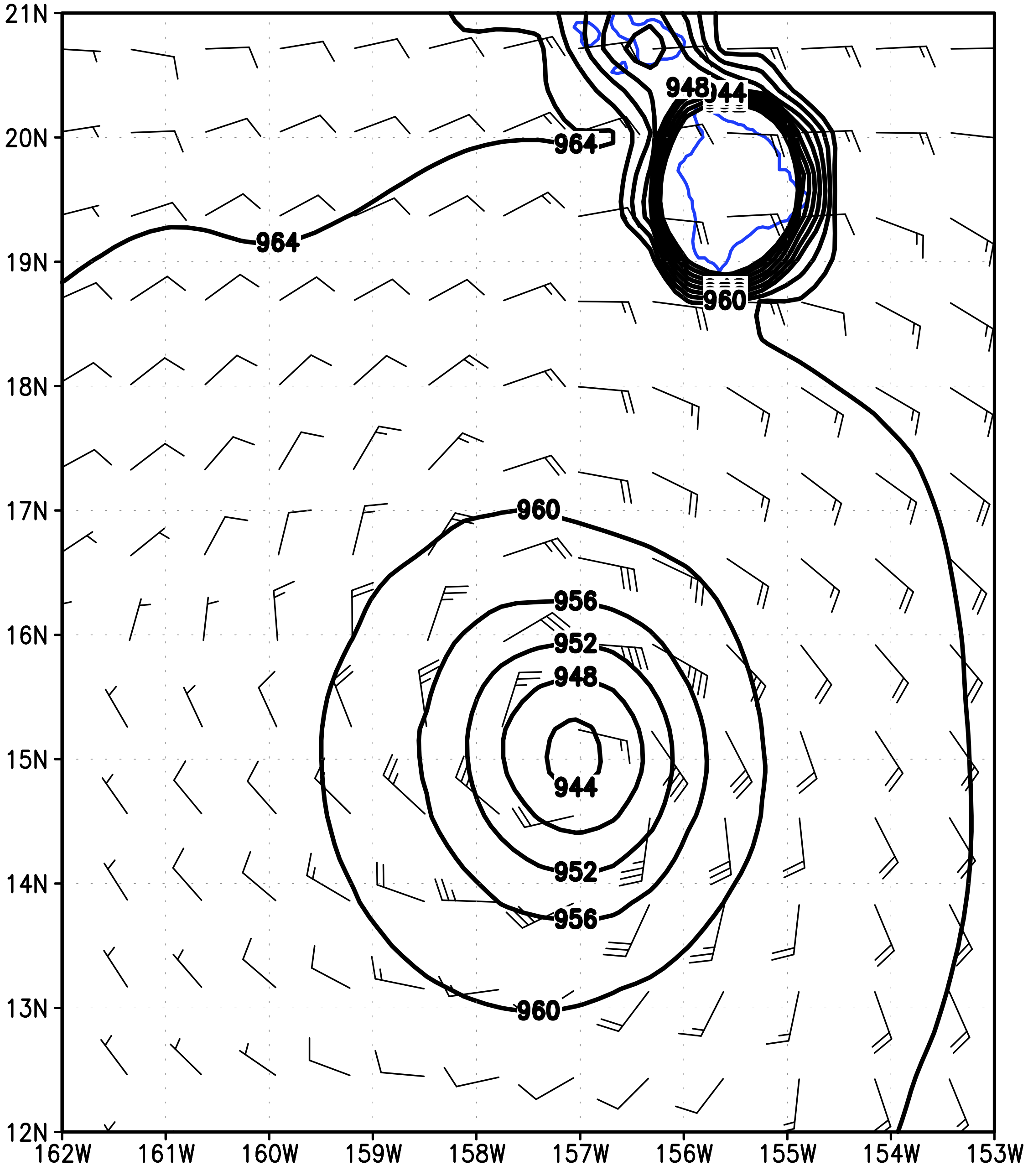
Cost function profile for winds



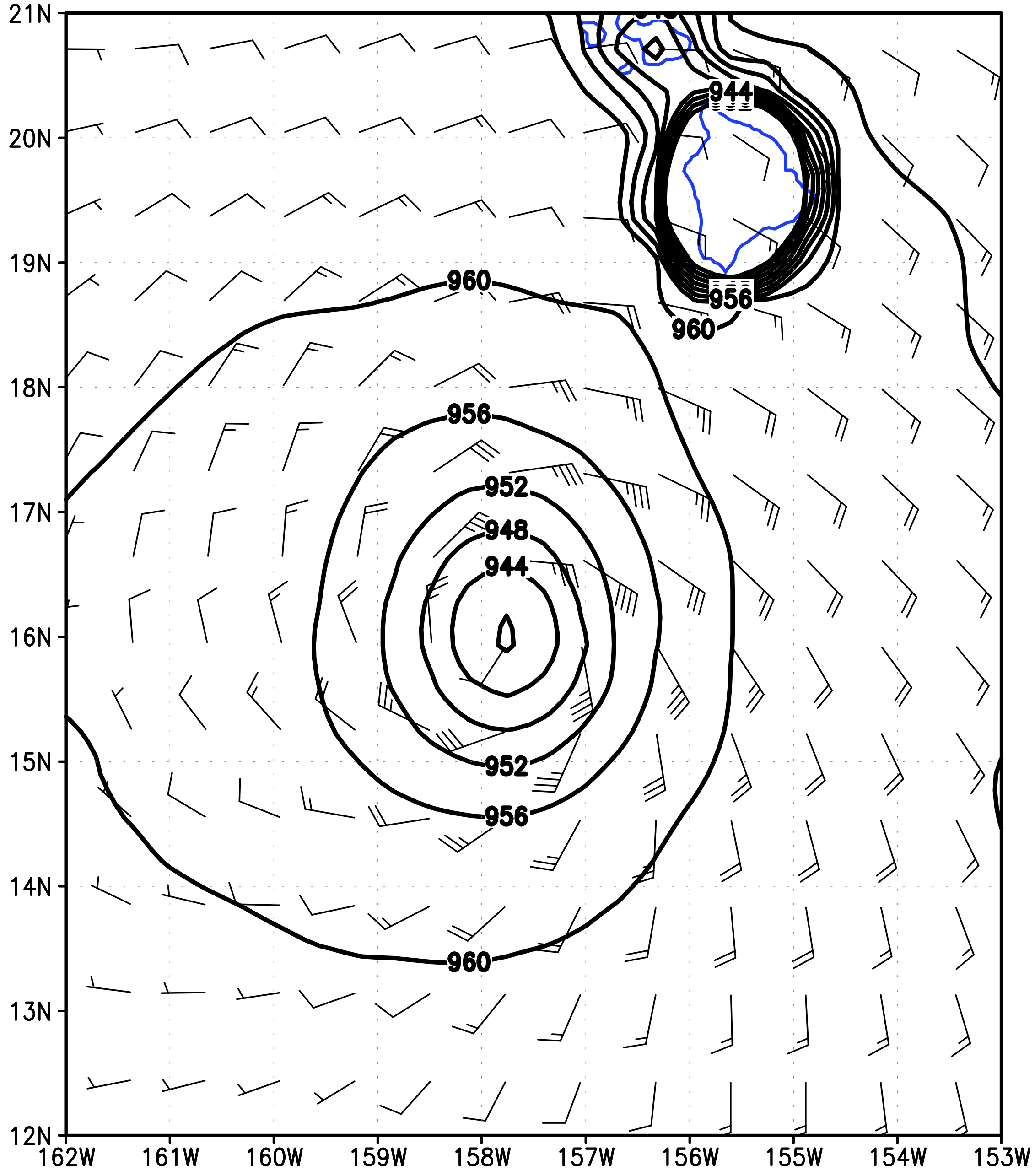
Cost function profile for temperature



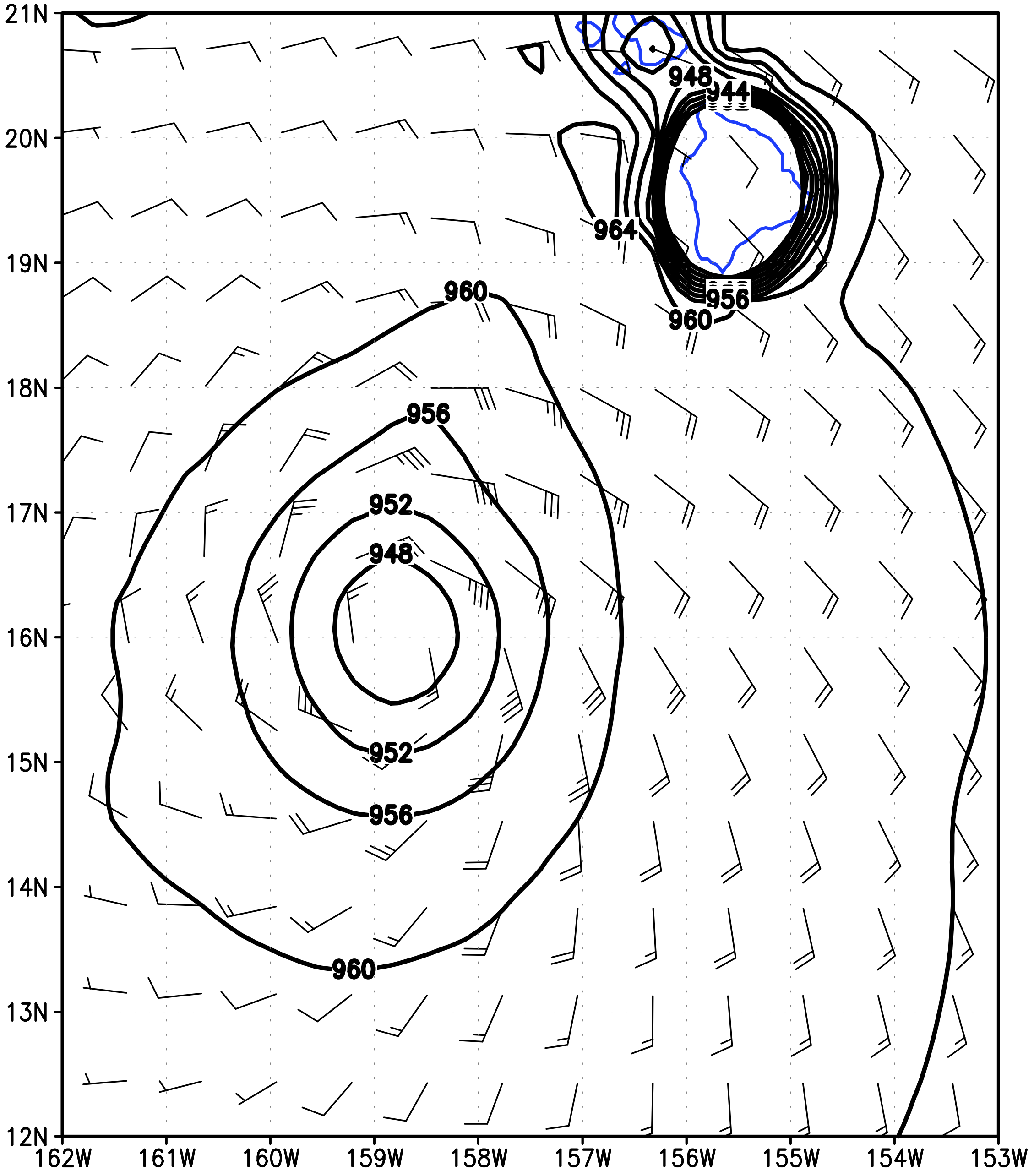
Unperturbed initial conditions



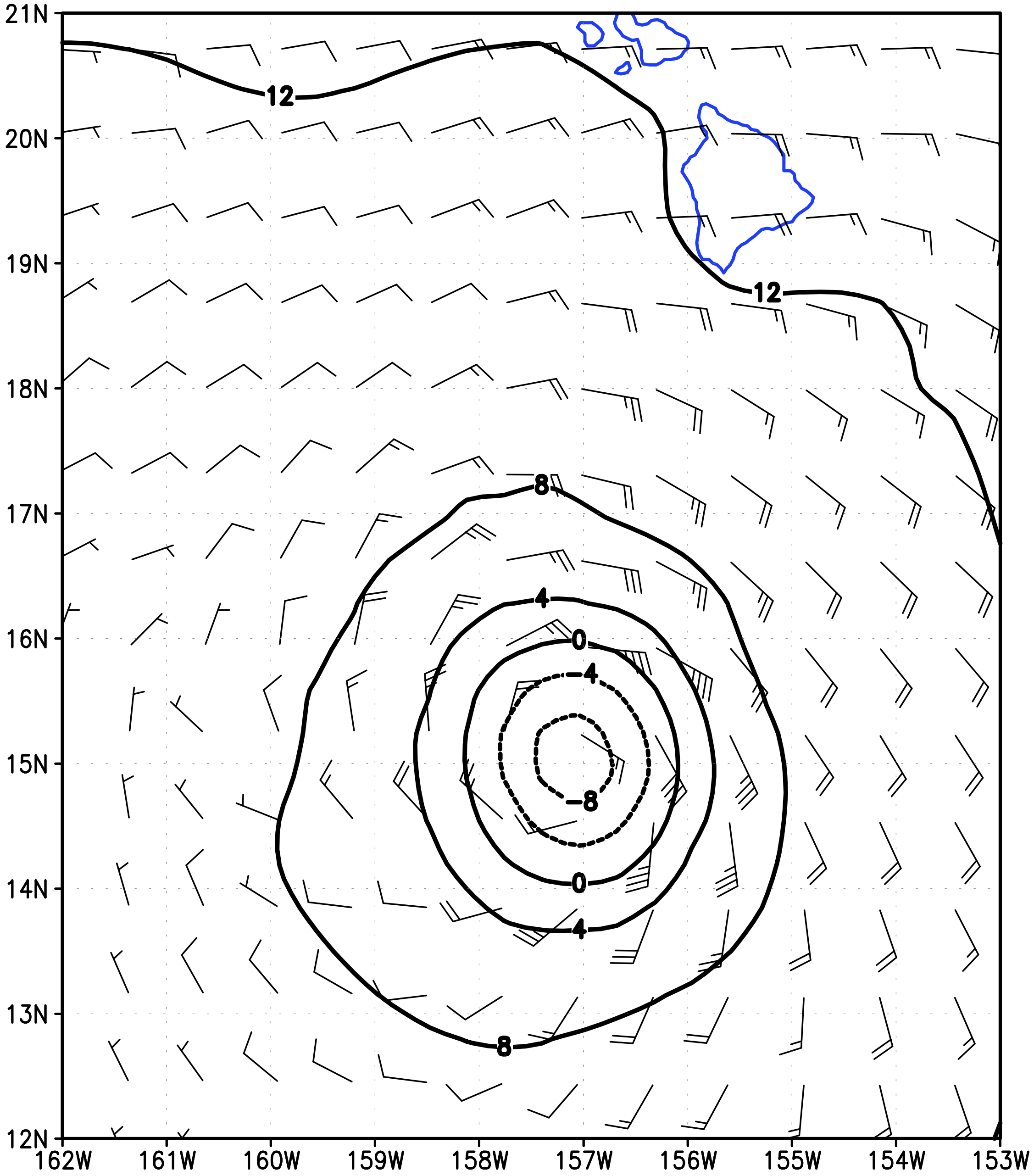
Unperturbed 6 hour forecast



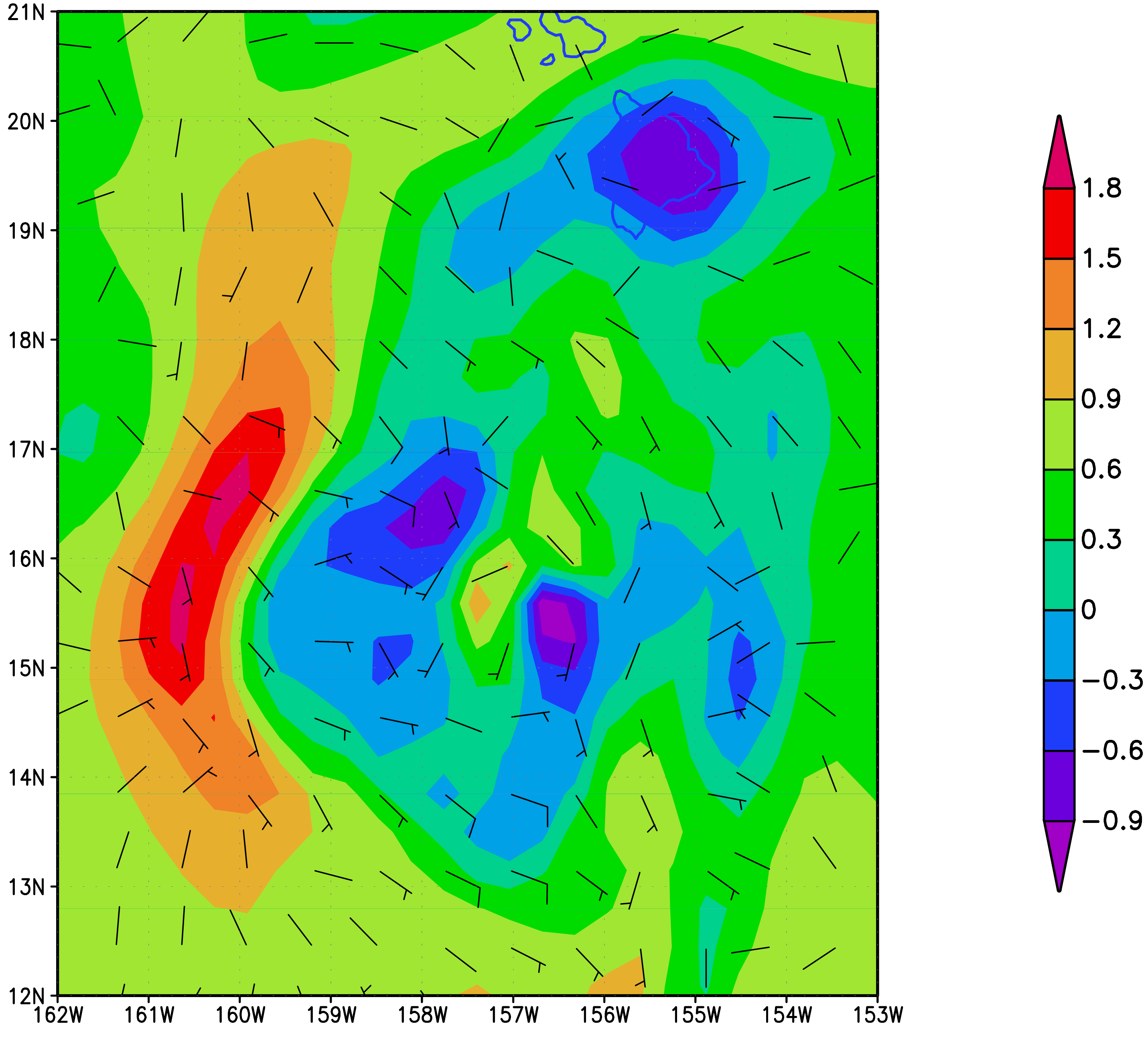
Perturbed 6 hour forecast



Perturbed initial conditions



Perturbation



Phase 2 objectives

- **Refinements to the 4d-VAR study**

  Use higher resolution, more accurate version of MM5

  Examine the effect of different lead times on the size of the perturbations

  For the goal, include only the energy of the mismatch in some region

  Modify the control vector so that only certain types of perturbations might be allowed, but allow perturbations continuous in time

  Study the effect of model and perturbation error

- **Top level system design**

  Use the energy of the perturbations in the hurricane case studies to do a scale analysis of the on orbit system components based on the solar reflector concept