IMPLEMENTATION OF A CLIMATE MODEL ON THE IBM-SP

Ravi S Nanjundiah
Mathematics and Computer Science Division
Argonne National Laboratory
9700 South Cass Ave., Argonne, IL 60439-4844

IMPLEMENTATION OF A CLIMATE MODEL ON THE IBM-SP

- How is Climate Studied?
- What is a Climate Model?
- Details of the NCAR CCM2.
- Implementation of CCM2 on the IBM-SP.
- Performance Issues.
- Future Work with CCM2.

How is Climate Studied?

1. Data Analysis

   Study of Data from Satellites, Ground Stations, Oceanographic Soundings, Ice Cores, Flood Records, Excavations (fossils) etc

2. Modelling Studies

   Statistical Models: Fitting statistical models to available data

   Numerical Models: Solving Physical/Fluid Dynamics Models to study/simulate climatic trends

Data Analysis/statistical models cannot be used for sensitivity studies (like CO2 doubling) for multiple scenarios.

Hence we use Numerical Models to study climate.

NUMERICAL CLIMATE MODELS

These use equations of momentum, energy and mass conservation to simulate the earth's atmosphere and climate.

A Numerical Climate Model has two major sub-components:

Dynamics

This part of the model deals with the dynamics viz : velocities, pressure gradient calculations, advection i.e. state of the atmosphere.

Physics

This part of the model deals with variables that affect the state of the atmosphere viz. solar radiation, longwave radiation, cloudiness, precipitation, surface energy balance.

The *Primitive Equation Model*

Co-ordinate System:

X direction is east-west (east positive)

Y direction is north-south (north positive)

Z direction vertical

Choice of Co-ordinates in the Vertical:

- Distance as a vertical co-ordinate
- Pressure as a vertical co-ordinate
- Non-dimensional Vertical co-ordinate (σ)
- Hybrid Co-ordinate

The equations are :

Numerical Solution

These are coupled non linear PDEs.

We need to solve them numerically.

Solving them implies:

- Marching in time (temporal discretization).

- Calculating in space at each time step (spatial discretization)

Spatial Discretization

We can use

1. Finite Difference Methods

2. Spectral Methods.

to discretize spatially

<u>Finite Difference Techniques:</u>

Divide the domain (globe) into a mesh and describe variables on this mesh.

Describe derivatives as differences of neighbouring points.

CCM2 uses finite difference in the vertical direction

All Physics Calculation are done on a mesh.

<u>Spectral Techniques:</u>

Describe a variable as a combination of spatial waves.

CCM2 uses spectral techniques to calculate state variables

SPECTRAL TECHNIQUES

Initial Conditions/Boundary Conditions/Output/Physics Calculations of the Model is on gridpoint space.

Hence the need to convert

Gridpoint ——> Spectral ——> Gridpoint

At every step

The Gridpoint to Spectral is done in two steps:

1. Gridpoint to latitude-spectral space using Fourier Transform

2. Latitude-spectral to pure spectral using legendre Transform

A reverse process occurs in Spectral ——> Gridpoint conversion.

Note: The calculations of T,U,V are done in spectral space. All dynamics calculations for moisture Q is done on gridpoint space alone.

Spectral Algorithm

Any variable $\Psi(\lambda, \mu)$ can be represented by a truncated series in spectral space as:

$$\Psi(\lambda, \mu) = \sum_{m=-M}^{M} \sum_{n=|m|}^{\mathcal{N}(m)} \Psi_n^m(\mu) e^{im\lambda}$$

M is the highest Fourier wavenumber in e-w; $\mathcal{N}$(m) is the highest associated Legendre Polynomial for wavenumber m; N highest degree of Polynomial for m=0 and K = highest degree of ALP; For Triangular Truncation M = N = K;

$\mathcal{N}(m) = min(N + |m|, K)$

The conversion of Gridpoint to Spectral Space occurs in two steps:

- FFT's to convert from Gridpoint to latitude-wavenumber space;
- Legendre Transform to convert from l-w to pure wavenumber space.

Fourier Transform

The co-efficients of spectral representation are given by:

$$\Psi_n^m = \int_{-1}^{1} \frac{1}{2\pi} \int_0^{2\pi} \Psi(\lambda, \mu) e^{-im\lambda} d\lambda P_n^m(\mu) d\mu$$

The inner integral (over λ) represents a fourier transform:

$$\Psi^m(\mu) = \frac{1}{2\pi} \int_0^{2\pi} \Psi(\lambda, \mu) e^{-im\lambda} d\lambda$$

This is performed using a FFT routine.

Legendre Transform

This is used to convert data from latitude -wavenumber space to spectral space (to obtain spectral co-efficients)

This is performed using Gaussian Quadrature:

$$\Psi_n^m = \sum_{j=1}^{J} \Psi^m(\mu_j) P_n^m(\mu_j) w_j$$

where μ_j denotes the Gaussian grid points in n-s direction; w_j the Gaussian weights at μ_j and J the number of Gaussian grid points from pole to pole.

Gaussian Grid points are given by the roots of the polynomial $P_J(\mu)$

Gaussian Weights are given by:

$$w_j = \frac{2(1-\mu_j^2)}{[JP_{J-1}(\mu_j)]^2}$$

And the weights are chosen such that:

$$\sum_{j=1}^{J} w_j = 2.0$$

Symmetry about equator exploited for pole to pole summation and actual summation done from pole to equator only; by calculating the symmetric and anti-symmetric components of Ψ_i^m

Inverse Transform to Physical Space

After updating variables at step n+1. The variables are transformed back to physical space.

This is done in two steps:

1. Inverse Legendre Transform

   To Transform from Wavenumber space to wavenumber-latitude space:

   $$\Psi^m(\mu) = \sum_{n=m}^{\mathcal{N}(\Updownarrow)} \Psi_n^m P_n m(\mu)$$

   This is done as a vector product over n.

2. Conversion from w-l to lat-long space

   $$\Psi(\lambda, \mu) = \sum_{m=-M}^{M} \Psi^m(\mu) e^{im\lambda}$$

   This is done using FFT routine (backward FFT).

Semi-Lagrangian Method

Unlike ζ, T, η, q calculations are done in entirely in physical space.

Semi-Lagrangian tech. implies estimation of trajectories of parcels arriving at a grid point (the arrival point).

The moisture conservation equation (excluding sinks and source):

$$\frac{\partial q}{\partial t} + V \cdot \nabla q + \dot{\eta}\frac{\partial q}{\partial \eta} = 0$$

The semi-Lagrangian Calculations are done in two steps:

1. Horizontal direction

2. Vertical direction

The steps are:

1. Determine the mid-points of the trajectory. (iterative)

2. Determination of the departure point

3. Determination of specific humidity at the departure point using interpolation techniques. This becomes the value at arrival point.

PHYSICS CALCULATIONS

Physics calculations include:

1. Radiation Calculations
2. Estimation of Precipitation
3. Estimation of Cloudiness
4. Surface processes (temperature, wetness, fluxes).
5. Updating the temperature over ocean from climatological datasets.

All Physics calculations involve computation in the vertical alone. There are no horizontal dependencies

Radiation Calculations

Radiation calculations can be catogorised as:

Shortwave (solar) radiation

Longwave (infra-red) radiation

Shortwave Calculations

Includes the effects of diurnal (day and night) and annual (seasonal) variations.

Shortwave (incoming solar radiation) is divided into 18 spectral intervals and δ-Eddington approximation used to calculate transmissivity and absorptivity of each layer. Effects of molecular and droplet scattering and effect of clouds are also included. Absorption by O_3, H_2O and CO_2 and O_2 are also included.

Longwave Calculations

Uses the method of emissivity and absorptivity. Absorptivity calculations include the effects of H_2O, CO_2 and O_3. Effects of clouds in modifying long wave radiation is also included.

Clouds in the model are dependent on

1. relative humdidity

2. vertical velocity (upward velocity causes clouding)

3. atmospheric stability

4. convective precipitation rate

Types of clouds in the model: convective (cumulus) clouds, layered cloud, low-level marine stratus clouds.

Cumulus Convection Cloudinesss and precipitation occurs on scales smaller than the resolution of the model ($\sim$ 100 km). Hence needs to be parameterized. CCM2 uses 'moist adiabatic adjustment' process. Any layer which is unstable mixes with adjacent layers to produce rain.

Surface Processes

Fluxes: Are calculated using bulk aerodynamic formulae. The co-efficients are a function of the stability of the atmosphere.

Surface Temperature: The diffusion equation is solved for the sub-surface with surface fluxes (longwave, shortwave, latent heat and sensible heat) as the upper boundary condition.

RESOLUTION OF THE CCM2

Prognostic Variables: T, ζ, δ, q (and other tracers if specificed). T_s, W_s p_s etc.

Diagnostic Variables: $\dot{\eta}$, Rain, Snow etc.

At T-42 resolution :

Number of Latitude Points: 64

Number of Longitude Points: 128

Number of Levels: 18

Timestep : 20 minutes

Radiation Calculations at: 60 minutes

Emissivity/Absorptivity Calculations at: 12 hours.

PARALLEL IMPLEMENTATION OF CCM2

Parallel Implementation is done by 'decomposing data' over processors.

Commonly Used method of Decomposition is 'Domain Decomposition'.

Decompose the globe into smaller regions and assign each such region to to a processor (in grid point space).

In spectral space: Assign calculation of some of the spectral coefficients to each of the processors.

Note: The processors need to communicate with each other at appropriate intervals for the computation to be identical to that of a sequential simulation. This is an overhead involved in parallel computing.

Methods of Domain Decomposition:

1. Decomposition by Latitude Alone (1-D)
2. Decomposition by Longitude and Latitude (2-D).

1-D decomposition

A set of latitude circles are allocated to a processor.

A latitudnal pair is assigned to a processor e.g. 30S and 30N would be on the same processor. Also helps in load balancing.

Smaller Number processors can be used with this decomposition.

Needs communication only for Legendre Tranform (lat) and SLT (lat)

2-D Decomposition

A array of latitude and longitude points are assigned to a processor.

2-D allows larger number of processors to be used. Also studies have shown that 2-D decomposition is more efficient.

Also uses latitudnal pairs while decomposing.

Needs communication for Fourier (long), Legendre(lat) transforms and SLT (lat and long).

Note: we do not decompose in the vertical. Tight coupling in radiation and cloud/precip calculations would cause high overhead of communication.

Performance Studies

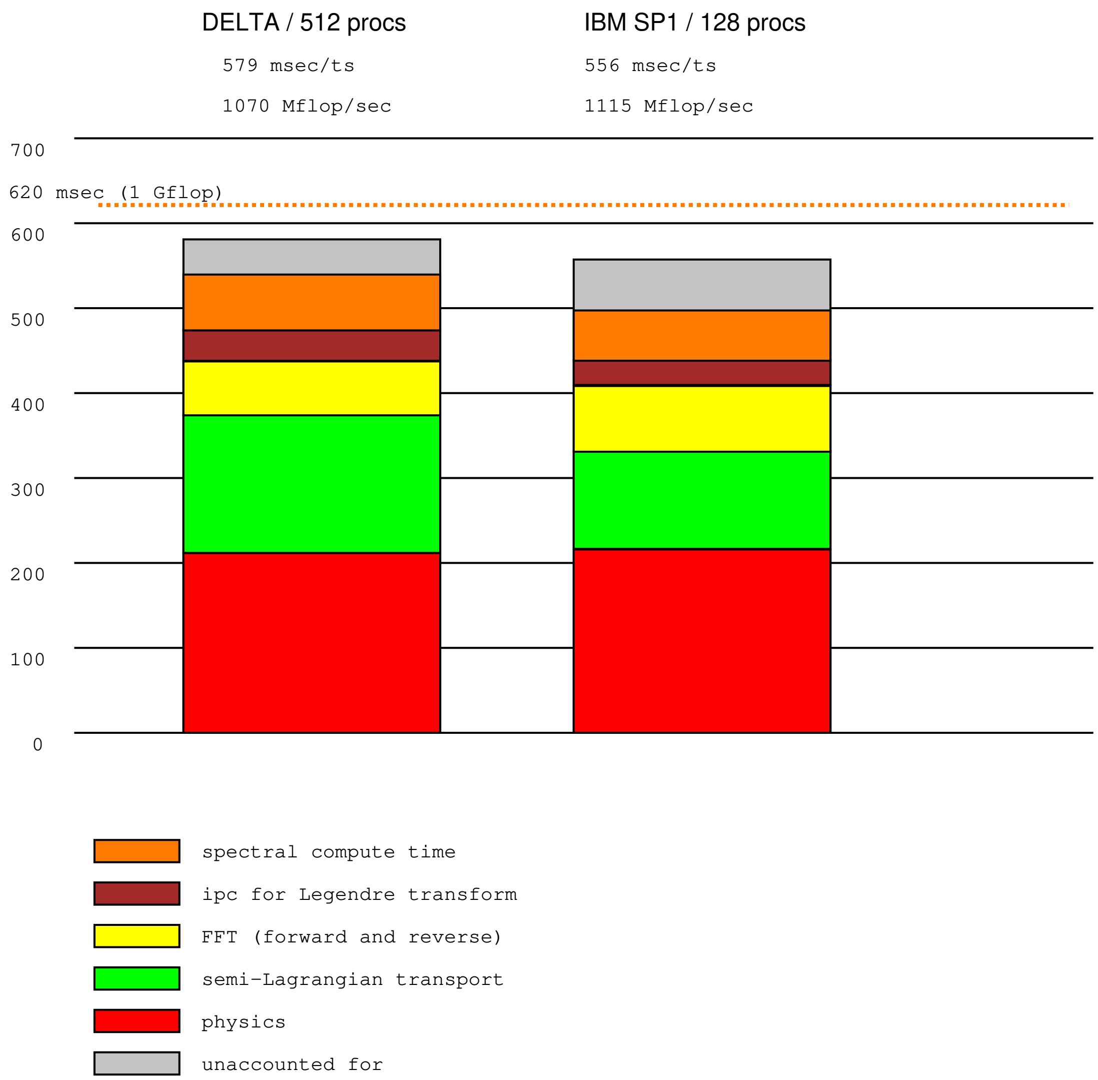
Peak Performance : 1.1 GFlops

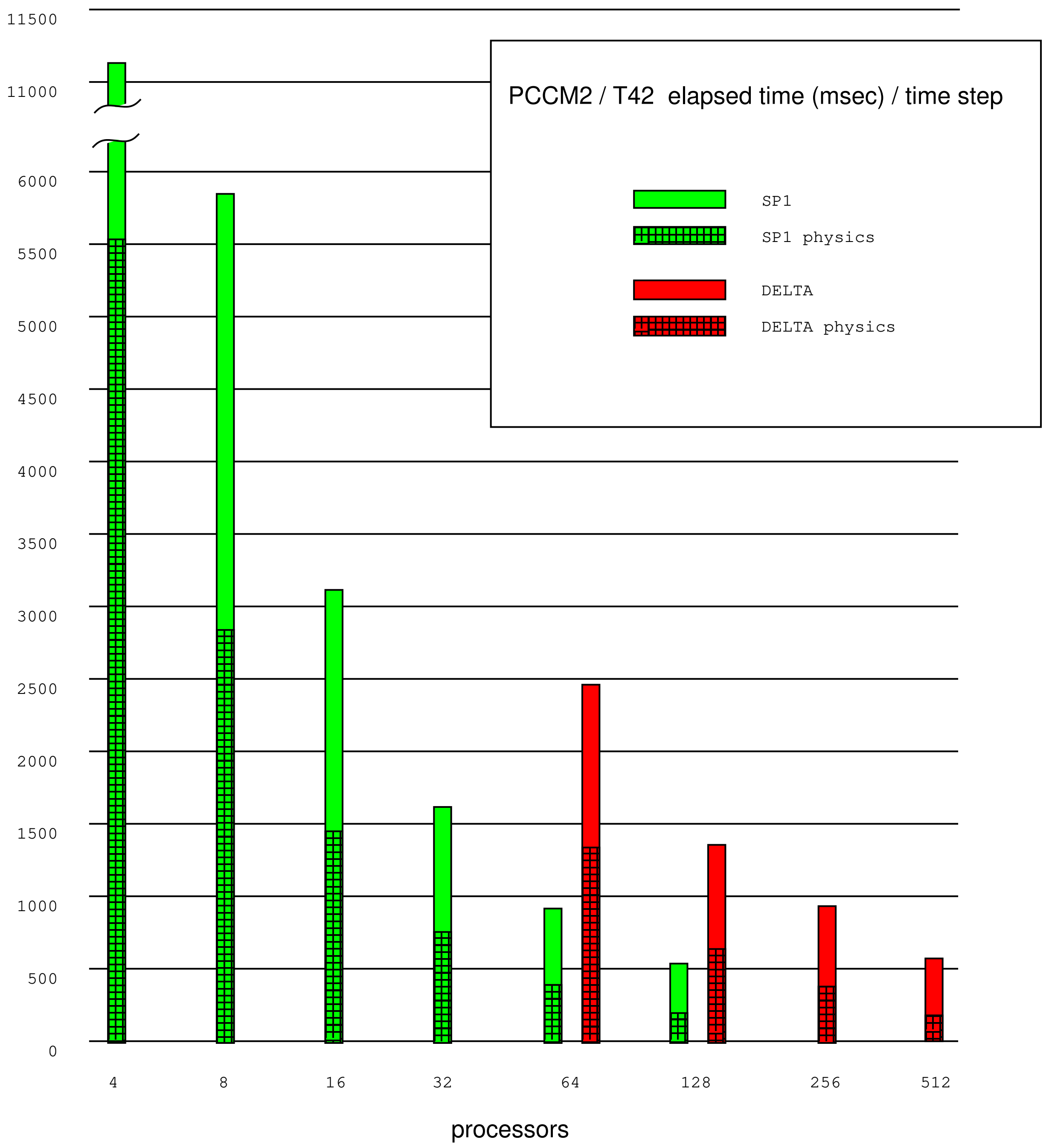
Physics	38%
SLT	20%
FFT	14%
LT	6%
Spectral Cal	11%

Load Imbalances: In Physics di-urnal variation

The pairing of latitudes from opposites parts of equator nullifies the seasonal effect of polar winter/summer

Elapsed time for average PCCM2 time step at T42 resolution




PCCM2 / T42 elapsed time (msec) / time step
SP1
SP1 physics
DELTA
DELTA physics
11500
11000
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
4
8
16
32
64
128
256
512
processors

SUMMARY

- Climate Model (CCM2) successfully implemented on IBM SP

- Load Imbalances studied and Eliminated.

- Parallel Model used for climate studies

- Being Coupled to an Ocean Model for long range climate studies ($\sim$ 1000 years).