Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Institut für Physik der Atmosphäre

Fakultät II TU Berlin Institut für Mathematik

Universität Potsdam

Development of a Lagrangian Core for Climate Models

V. Grewe, R. Sausen, A. Stenke, DLR-Oberpfaffenhofen
H. Yserentant, C. Kamm, TU Berlin
S. Reich, S. Shin, Universität Potsdam

Project Overview

The aim of the project **LagKern** is the development of a Lagrangian core for climate models. Lagrangian approaches combine several advantages: They provide an adaptive resolution, are numerically non-diffusive, and enable the efficient treatment of a large number of different chemical species and tracers.

Phase I of the project is divided into two workpackages:

- **WP1: Development of Lagrangian dynamical core (TUB, UP)**
  Implementation of the Finite Mass Method on the rotating sphere
  Comparison with hybrid methods (Hamiltonian Particle-Mesh Method)
- **WP2: Lagrangian transport in a global climate model (DLR)**
  Implementation of spatial extension of air parcels according to the Finite Mass Method

Outlook for Phase II and III

- Phase II:
  - Merge and extend models to include both horizontal and vertical structure (see Shin and Reich)
  - Preparations for integration of a Lagrangian dynamical core into ECHAM: Analysis of forces derived with the Finite Mass Method and comparison with solution of primitive equations derived from spectral core
- Phase III:
  - Full implementation of Lagrangian dynamical core in the global climate model ECHAM5.MESSy
  - Evaluation of simulated climate (dynamics, hydrological cycle, tracer distributions)

WP1: The Finite Mass Method on the rotating sphere (TUB)

- Completely Lagrangian
- Discretize mass as superposition of packets with fixed masses
- Prognostic variables: position q_i and linear deformation H_i, including expansion, rotation, and shear, for each packet

$$\rho_i(x,t) = m_i \frac{\psi(y)}{area(H_i(t), y)},$$

where $y = y(x, q_i(t), H_i(t))$

- Use the same ansatz for other thermodynamic quantities
- Canonical formulation of kinetic and potential energies leads to Hamiltonian system
- Pressure forces acting on a packet are calculated from total density within its area
- Mass, energy, and generalized angular momentum are conserved

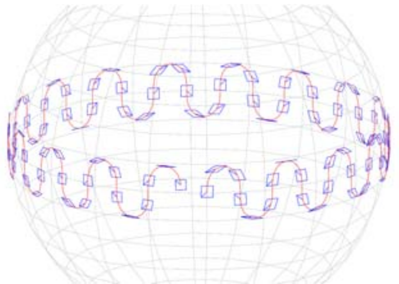


Figure: Evolution of single packet over 100 days. Packet has size of 400 km and starts at equator with poleward velocity of 10 m/s. No pressure forces.

- Remaining goals for phase I:
  - Run standard tests for shallow water equations on rotating sphere
  - Compare to Hamiltonian Particle-Mesh Method

WP1: Hamiltonian particle-mesh simulations for a non-hydrostatic vertical slice model (UP)

- **Hamiltonian Particle-Mesh Method (HPM):**
  - A set of particles: $\mathbf{X}_k(t) = (X_k(t), Y_k(t)), \quad k = 1, \ldots, N$
  - Fixed Eulerian grid (Mesh): $x_{i,j} = (x_i, y_j) = (i \cdot \Delta x, j \cdot \Delta y), \quad i, j = 0, \ldots, M$
  - Mesh-defined densities from the particle nearby mesh points:

$$\rho(x_{i,j}) = \sum_k m_k \psi_{i,j}(\mathbf{X}_k(t))$$

  - Thermodynamic variables approximated on a regular array of mesh points
  - Forces at particle positions are approximated from the array of mesh-defined values
  - Particles carry a velocity, position, mass and potential temperature
  - Regularization does not interfere with a hydrostatic reference state
- **Non-hydrostatic 2-D slice model:**
  - A "mass" coordinate is used for the vertical so that the grid can represent hydrostatic balance well
  - Test case: Motions of two bubbles

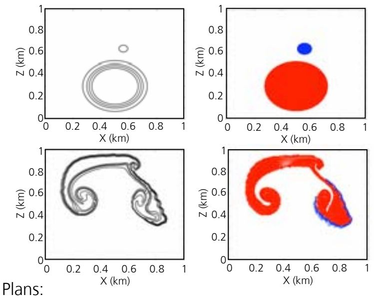


Figure: Potential temperature and particles with temperature perturbation at the initial instant (upper panel) and at 10 min (lower panel).

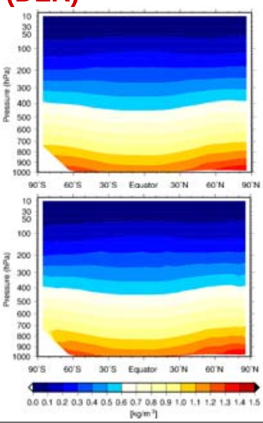
- Future Plans:
  - Simulations of orographic flow
  - Initialization test on the sphere using shallow water equations

WP2: Lagrangian Transport in a global climate model (DLR)

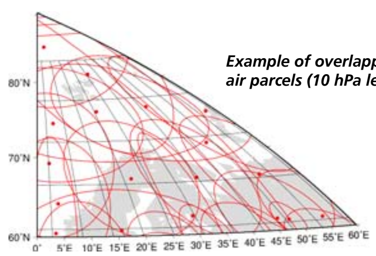
- Basic model tools:
  - Underlying global climate model **ECHAM5.MESSy** (spectral dynamical core)
  - Lagrangian transport model **ATTILA:**
    approx. 500000 air parcels of constant mass, no spatial extension
    advection of air parcels by simulated 3d wind field
- Implementation of spatial extension of air parcels according to Finite Mass Method:
  - prognostic variables: position of particles $\mathbf{q}_i$ and linear deformation $\mathbf{H}_i$

$$\mathbf{q}_i'(t) = \mathbf{v}(\mathbf{q}_i(t), t), \quad \mathbf{H}_i'(t) = (\nabla \mathbf{v})(\mathbf{q}_i(t), t)\mathbf{H}_i(t)$$

  - velocity field $\mathbf{v}$ taken from climate model
  - total mass density given by overlapping air parcels: $\rho(\mathbf{x}, t) = \sum_{i=1}^{N} m_i \psi_i(\mathbf{x}, t)$
- Remaining goals for phase I:
  - Evaluation of characteristics of air parcels (size and shape) in global climate model, and analysis of impact on simulated tracer distribution



Left Figure: Zonal mean density distribution as simulated with the climate model ECHAM5.MESSy (upper panel) and as calculated by the Lagrangian air particles using the Finite Mass Method (lower panel).



Example of overlapping air parcels (10 hPa level).