Reconstruction of Stratospheric Ozone Dynamics with MPAS and a High Resolution Transport Model on a Rotated Sphere

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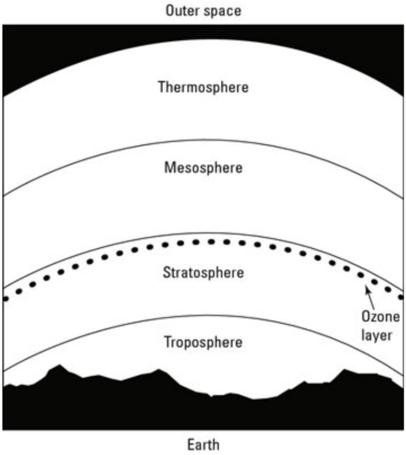
Outline

1. Introduction to Stratospheric Ozone
2. Model for Prediction Across Scales (MPAS)
3. Lagrangian Advection and Future Work

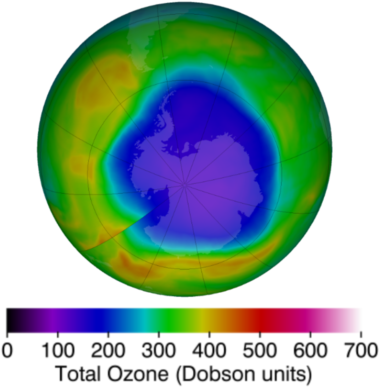
Stratosphere and Ozone Layer

- Stratosphere (10 - 50 km)
  - Temperature increases with altitude
  - Dry climate with little convection or water vapor
- Ozone Layer (20 - 40 km)
  - Located within stratosphere
  - Absorbs UVB which causes cancer, cataracts, etc.
  - Project focus on stratospheric ozone (not ozone from pollution)

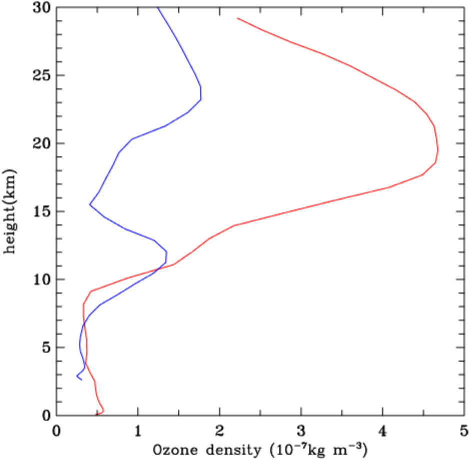


Ozone Hole

- Dobson unit
  - Measure of total ozone concentration in a column of the atmosphere
  - 1 DU = 0.01 mm thickness of ozone compressed at STP
- Ozone hole defined by values of total ozone less than 220 Dobson units
- Created by complex interaction between stratospheric chemistry and dynamics



Ozone Density



- Point inside polar vortex
- Point outside of polar vortex

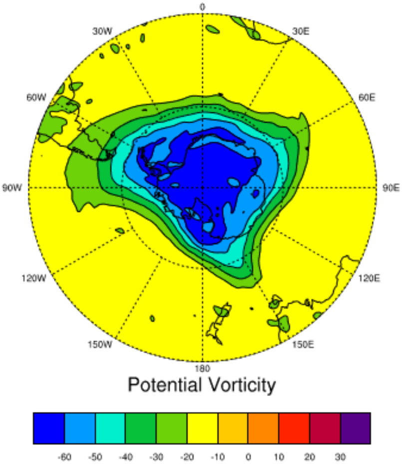
Ozone Hole: Chemical Causes

- Chemistry accounts for depletion of ozone
- CFCs (and other ODSs) escape from refrigeration and propellent devices
- Small portion of CFCs transported to the stratosphere above the pole
- UV rays separate Cl compound
- Single Cl destroys hundreds of ozone molecules in the spring

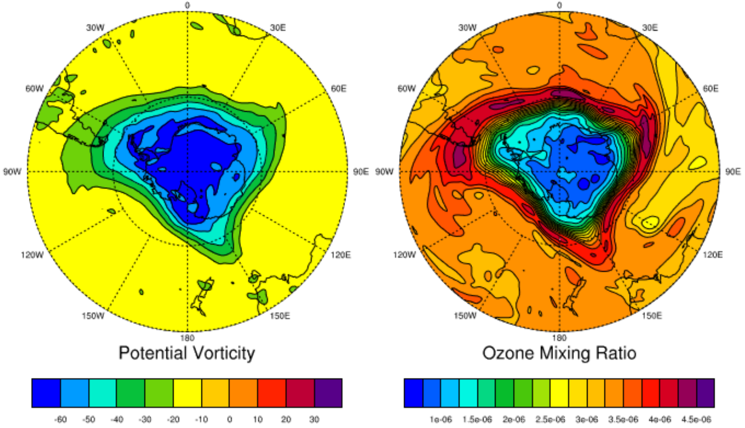
Polar stratospheric clouds

Ozone Hole: Dynamical Causes 1/3

- Dynamics account indirectly for destruction of ozone
- The polar vortex prevents exchange of heat between air inside and outside the vortex
- The dynamics of the polar vortex are identified by a variable called potential vorticity
- The potential vorticity accounts for the wind vector (curl of horizontal velocity) and planetary rotation

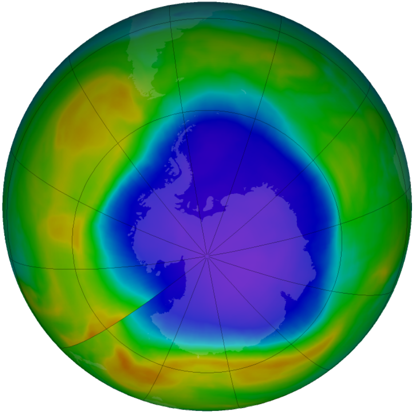


Ozone Hole: Dynamical Causes 2/3

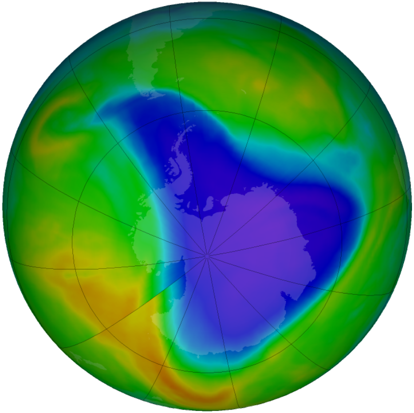


- Distribution of potential vorticity and ozone mixing ratio on the isentrope 475 K

Ozone Hole: Dynamical Causes 3/3



November 3, 2018



November 6, 2018

Research Questions

- Simulate ozone over the south pole from November 3, 2018 to November 8, 2018
- Use wind velocities generated by MPAS to reconstruct the distribution of ozone on a rotated grid
- Analyze the impact of horizontal transportation on the distribution of ozone

MPAS

- MPAS is a global Model for Prediction Across Scales
- We are using MPAS to simulate real atmospheric dynamics including ozone distribution over an unstructured global grid with variable resolution.
- We will use the winds simulated by MPAS to reconstruct the fine scale structure of ozone at higher resolution using isentropic transport model on a rotated grid

Equations Solved by MPAS

- Horizontal Momentum Equation for horizontal wind velocity: (v)
- Vertical Model Equation for vertical wind velocity: (w)
- Thermodynamic Equation: (θ)
- Continuity Equation for density: (ρ)
- Equation for Moisture: (q) water vapor, clouds, rain, ice ,etc

What We Have Added

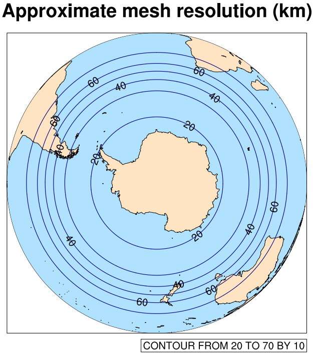
- Horizontal Momentum Equation for horizontal wind velocity: (v)
- Vertical Model Equation for vertical wind velocity: (w)
- Thermodynamic Equation: (θ)
- Continuity Equation for density: (ρ)
- Equation for Moisture: (q) water vapor, clouds, rain, ice ,etc

- **Equation for mixing ratio of ozone**

$$r = \frac{\rho_{O3}}{\rho}$$

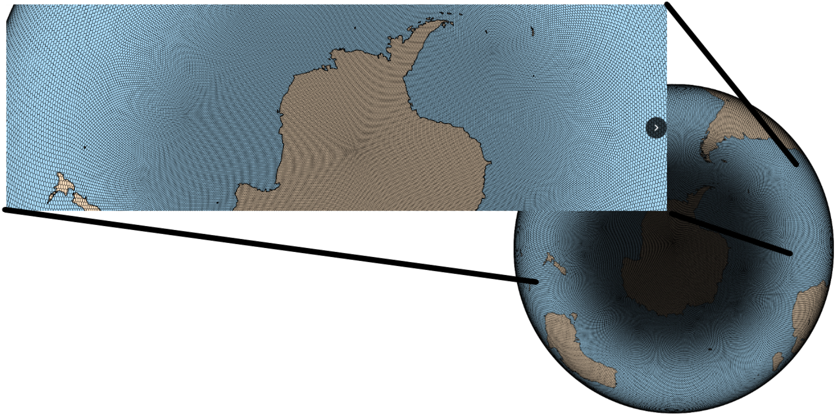
Variable Resolution

- MPAS can use a fixed or variable resolution, we use variable resolution
- MPAS is an Eulerian model that solves the PDEs governing atmospheric dynamics



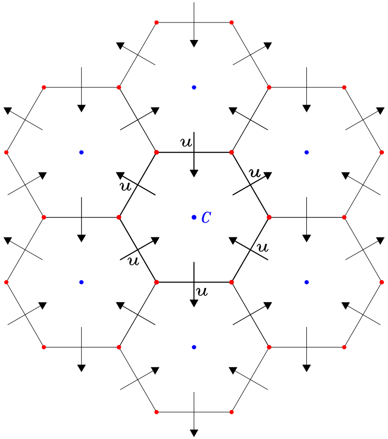
Our Uses in Grid Structure

- We rotate the grid to have the best resolution at the south pole
- Benefit of variable resolution - better resolution at a specific point



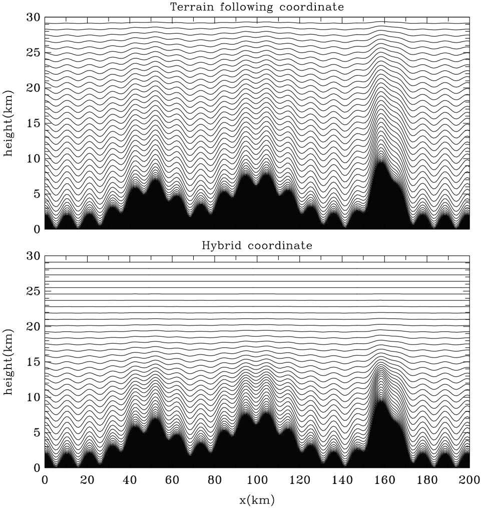
Spatial Discretization

- MPAS is based on a centroidal voronoi meshes using C-grid staggering
- Can be uniform distribution of grid points or variable resolution



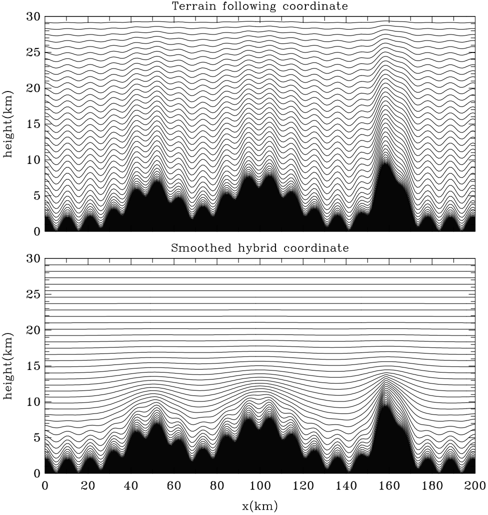
Vertical Grid Adjustments 1/2

- The vertical coordinate in MPAS is based on smoothed hybrid terrain following coordinate



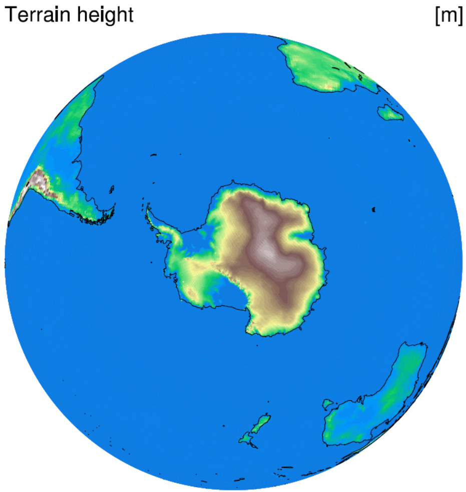
Vertical Grid Adjustments 2/2

- The vertical coordinate in MPAS is based on smoothed hybrid terrain following coordinate

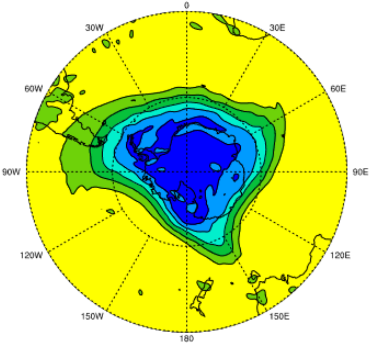


Initialization

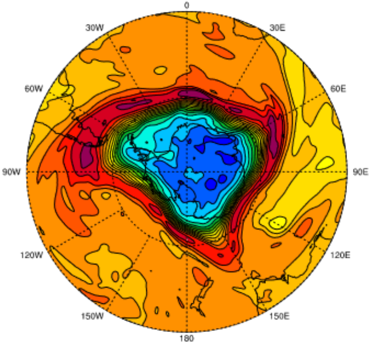
- Step 1: Interpolate static data to the horizontal MPAS grid.
  - This includes: topography, land use, vegetation, etc.



- Step 2: Populate time dependant data for initial conditions
  - Data used are global fields from the European Center for Medium-range Weather Forecasting (ECMWF): wind, pressure, temperature, ozone...
  - Interpolate this data in both horizontal and vertical to the 3-D MPAS C-grid.
  - This creates the initial condition to run MPAS



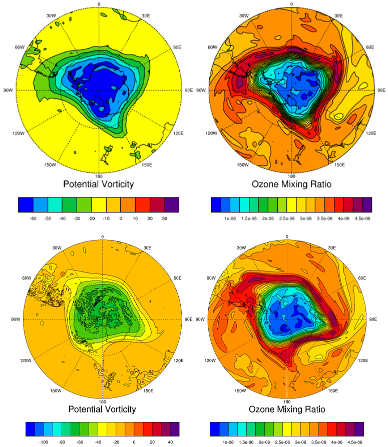
Potential Vorticity



Ozone Mixing Ratio

RUN MPAS!!

- Use parallel computing to predict the state of the atmosphere from 3 Nov at 00 UTC to 8 Nov 00 UTC from the ground to 30 km



Transport Equations

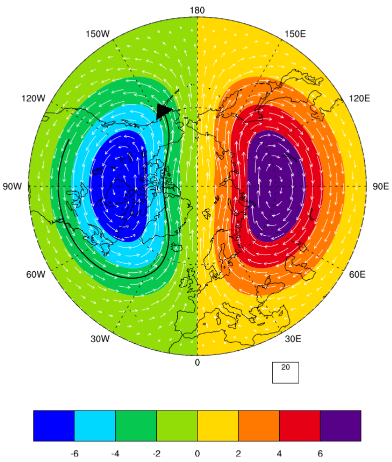
- The wind simulated by MPAS will be used to reconstruct ozone and PV fields at high resolution.

$$PV = -g\frac{\partial\theta}{\partial p}\left(\nabla_\theta \times \mathbf{V} + 2\Omega \sin\phi\right)$$

- The transport model uses the 4th order Runge-Kutta scheme to solve the following equations on isentropic vertical coordinates:

$$\frac{d\lambda}{dt} = \frac{u}{acos\phi}, \qquad \frac{d\phi}{dt} = \frac{v}{a}$$

- (λ, ϕ) are the spherical coordinates in longitude-latitude
- u, v are the eastward and northward velocities interpolated to isentropic levels
- a is the radius of Earth.


180
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60W
60E
30W
30E
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-6
-4
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180
150W
150E
120W
120E
90W
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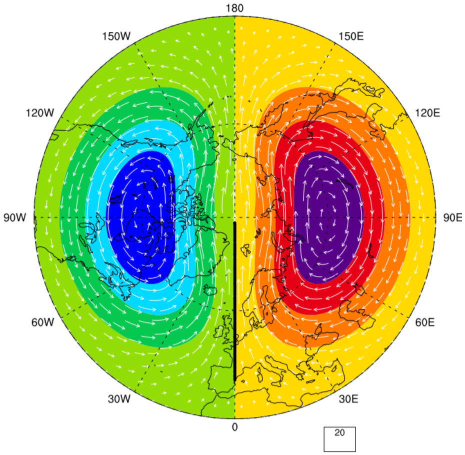
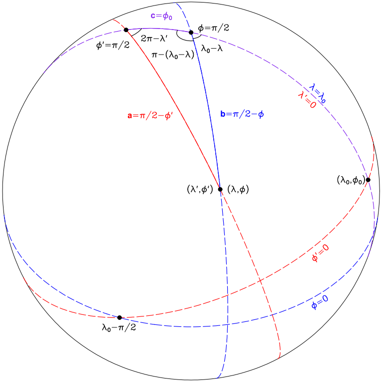
6

Lagrangian Advection and the Issue of Singularity



Geodesic Coordinate System

- (λ, ϕ) are the logitude-latitude coordinates of a given point
- (λ', ϕ') are the corresponding coordinates on the rotated sphere



- The sphere is rotated so that the start of a trajectory (λ_o, ϕ_o) is the origin of the rotated sphere $(\lambda' = 0, \phi' = 0)$

- Equations solved near the pole:

$$\frac{d\lambda'}{dt} = f'_\lambda, \qquad \frac{d\phi'}{dt} = f'_\phi$$

- The transformation between (λ, ϕ) and (λ', ϕ') is derived from the sine and cosine laws of spherical triangles:

$$\sin\phi' = \sin\phi\cos\phi_o - \cos\phi\sin\phi_o\cos(\lambda_o - \lambda)$$
$$\sin\phi = \sin\phi'\cos\phi_o + \cos\phi'\sin\phi_o\cos(\lambda')$$
$$\sin\lambda'\cos\phi' = -\sin(\lambda_o - \lambda)\cos\phi$$

Geodesic Equations 2/2

- The velocities in the rotated local geodesic coordinates $(f'_\lambda,\, f'_\phi)$ are computed from the eastward and northward velocities $(u,\, v)$:

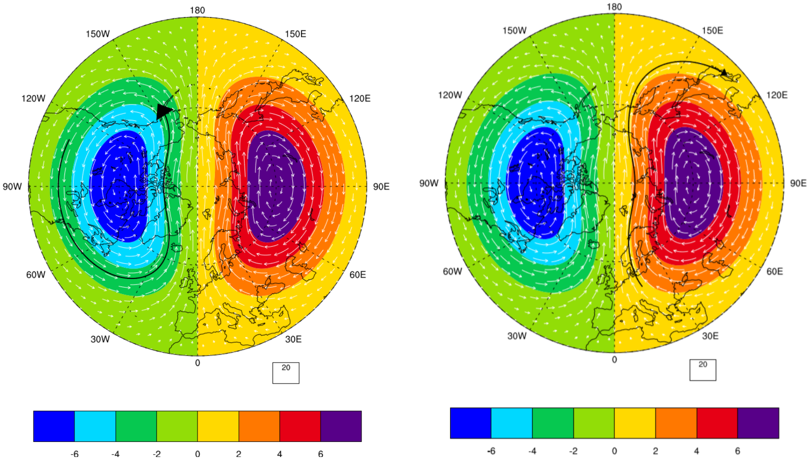
$$
\begin{aligned}
a f'_\phi \cos\phi' &= v\Big(\cos\phi\cos\phi_o + \sin\phi\sin\phi_o\cos(\lambda_o - \lambda)\Big) \\
&- u\sin\phi_o\sin(\lambda_o - \lambda)
\end{aligned}
$$

$$
\begin{aligned}
a f'_\lambda \cos\phi' \cos(\lambda') &= u\cos(\lambda_o - \lambda) + v\sin\phi\sin(\lambda_o - \lambda) \\
&+ a f'_\phi \sin\lambda' \sin\phi'
\end{aligned}
$$

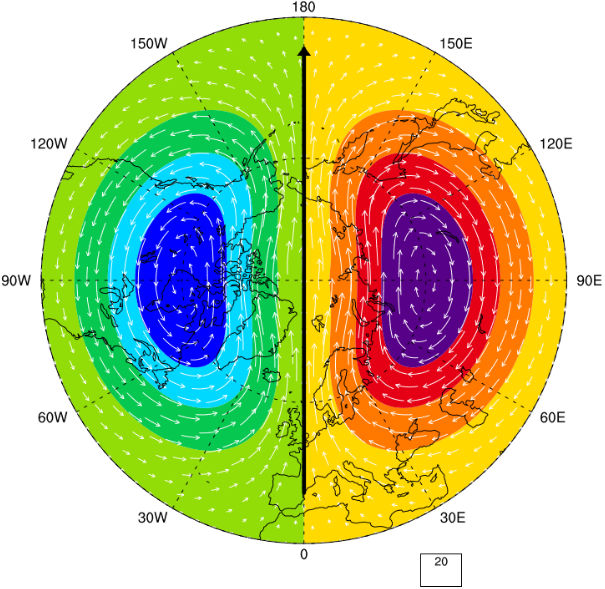
Transport Algorithm

- Starting at $(\lambda = \lambda_o, \phi = \phi_o)$, the algorithm is implemented as:
- If $|\phi_o| < 70^o$ update (λ, ϕ) on the unrotated sphere
- If $|\phi_o| \geq 70^o$ update (λ, ϕ) on the rotated sphere as follows:
  1. Rotated the grid so that $(\lambda' = 0, \phi' = 0)$ at (λ_o, ϕ_o)
  2. Use coordinate transformations to find (λ, ϕ) from (λ', ϕ')
  3. Interpolate (u, v) to the point (λ, ϕ)
  4. Use velocity transformations to compute (f'_λ, f'_ϕ) from (u, v)
  5. Update (λ', ϕ') using (f'_λ, f'_ϕ)
  6. Repeat steps 2 trough 5 for each RK4 sub-step
  7. At the exit of the RK4 loop, use coordinate transformations to find (λ, ϕ) from (λ', ϕ') and move to the next timestep.

Effect of the Geodesic Coordinate System 1/2



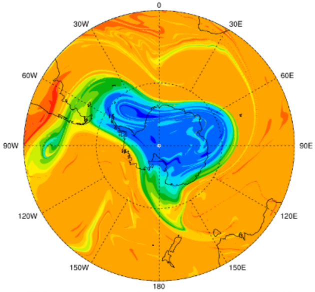
Effect of the Geodesic Coordinate System 2/2



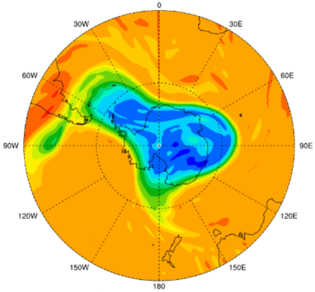
Summary

- Introduction to Ozone
- Model for Prediction Across Scales
- Lagrangian Advection

Preliminary Results and Future Work



PV reconstructed at the isentrope 475 K



PV from ECMWF at the isentrope 475 K

- Implementing the data gathered from MPAS to run the Lagrangian Advection simulations to reconstruct ozone and potential vorticity and analyze the impact of isentropic advection on the transport of air from inside the ozone hole

Acknowledgements

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