Airships and Weather

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Introduction

- Weather hazards to airship operation
- Hazard mitigation
- Weather over complex terrain
  - Prediction
- Route planning and optimization
  - Severe weather avoidance
  - Finding favorable winds

Airship Weather Hazards

- Winds
  - Can equal or exceed the speed of travel
  - Turbulence and large eddies can cause problems
  - Wind gusts near ground have caused numerous airship accidents
  - Terrain-induced winds and turbulence
- Temperature extremes
  - Affects buoyancy and hence the ability to climb or descend
  - Super-stable near surface layers can disrupt landing attempts

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Airship Weather Hazards

- Icing
  - Loads the airship
- Precipitation (rain, snow, hail)
  - Loads the airship
  - Induced downdrafts can pose a serious hazard
  - Hail can damage the envelope
- Thunderstorms
  - Updrafts and downdrafts
  - Turbulence
  - Gust fronts
  - Precipitation
    - Heavy rain, hail

USS Shenandoah crashed in 1925 when caught in a storm over Ohio

Hazard Mitigation

- Airships are (usually) slow, underpowered, and large
  - High inertia
  - It may not be possible to take evasive actions at the last minute
- Avoid … Avoid … Avoid
  - Avoid takeoffs and landings in adverse weather
  - Avoid regions of adverse weather during flight
- Advance planning
  - Use detailed weather information and forecasts
  - Alternate routes and landing sites
- Constant monitoring and updates
  - Use detailed weather information and forecasts

However …

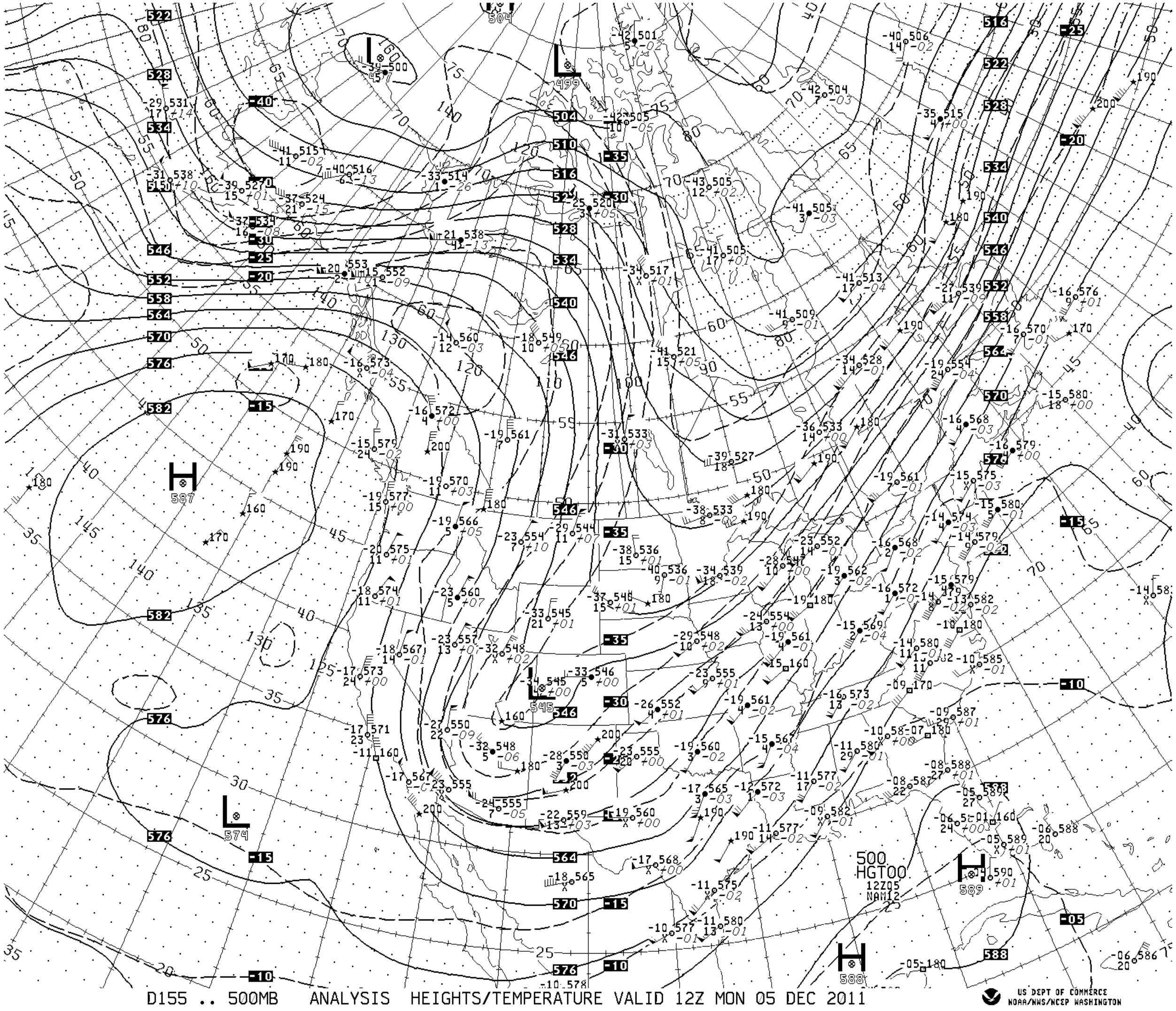
- Weather forecasting and analysis tools have significantly improved over the years
  - Higher resolution
  - Improved terrain representation
  - Improved physics
  - Improved computational performance
    - Operations on large parallel systems
- Observational systems have also improved
  - Satellite observations
  - Doppler radar
    - Ground-based
    - On-board
  - Automated observing systems
- Modern navigation systems
  - GPS

Weather Prediction over Arctic Regions

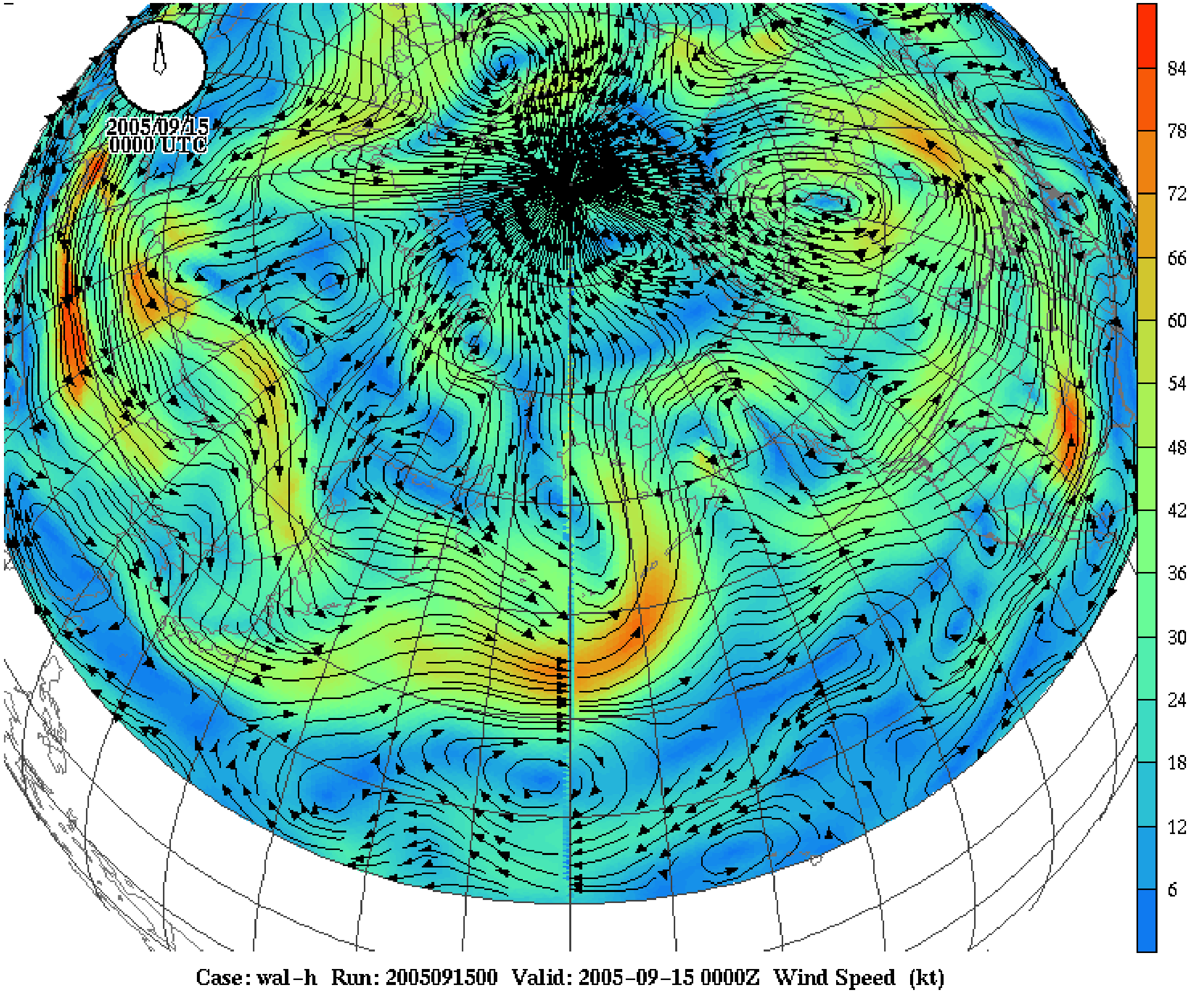
Weather over Arctic Regions

- Weather systems exhibit higher pressure gradients
  - Generate high winds
- Sudden changes in weather

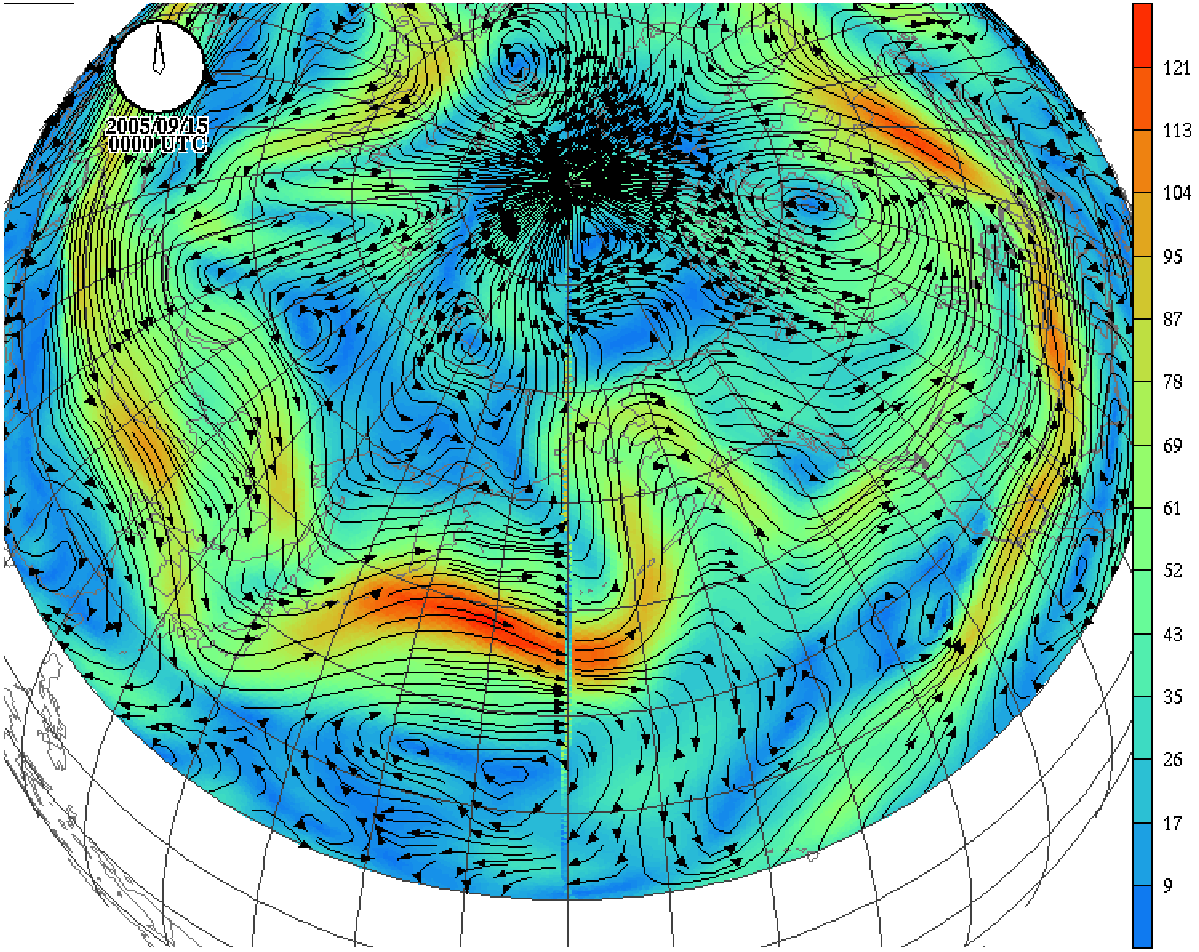
Gradients are Tighter over the Polare Regions



Winds at 500 mb (~ 5 km MSL)



Winds at 300 mb (~10 km MSL)



Case: wal-h Run: 2005091500 Valid: 2005-09-15 0000Z Wind Speed (kt)

Weather over Arctic Regions

- Weather over Arctic Regions, especially in the lower troposphere, is affected by terrain features
  - Elevation
  - Land-water boundaries
  - Snow and ice cover provides large contrasts in solar albedo
- Terrain-induced weather
  - Down-slope winds
  - Fog
  - Precipitation events
- Complex terrain poses special challenges to the weather forecaster/modeler

Fundamentals of Numerical Weather Prediction

Laws of Conservation start with

$$\frac{dQ}{dt} = \frac{\partial Q}{\partial t} + \vec{V} \bullet \nabla Q$$

If Q is conserved

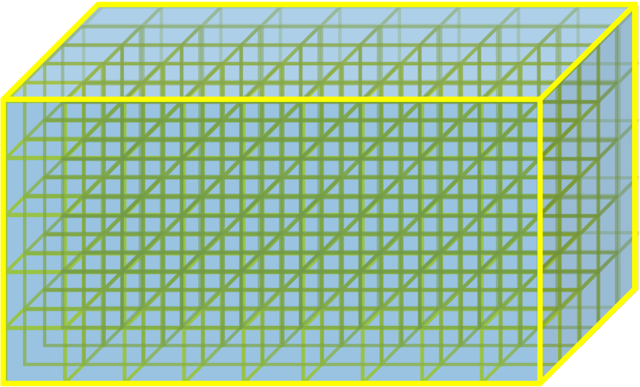
$$\frac{dQ}{dt} = 0$$

Hence

$$\frac{\partial Q}{\partial t} = -\vec{V} \bullet \nabla Q$$

Divide and Conquer

- The conservation equations have to be solved over the entire domain of interest, may be over the whole globe
- To make this feasible, we divide the domain into little bits within which we can assume that the properties do not change significantly



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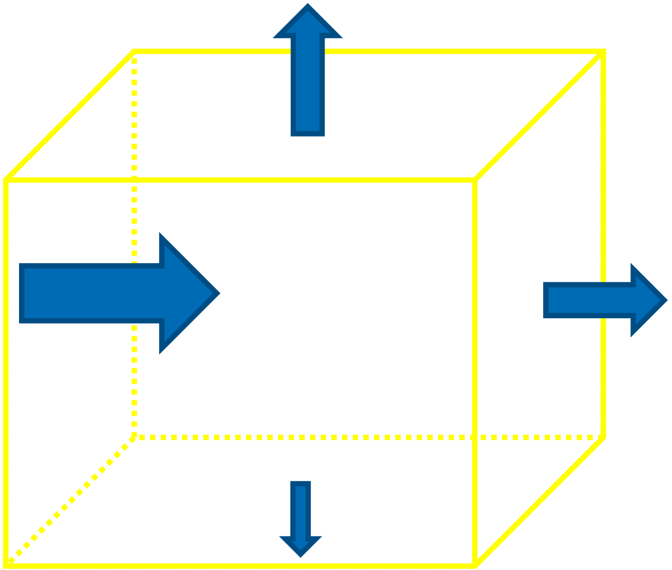
Divide and Conquer

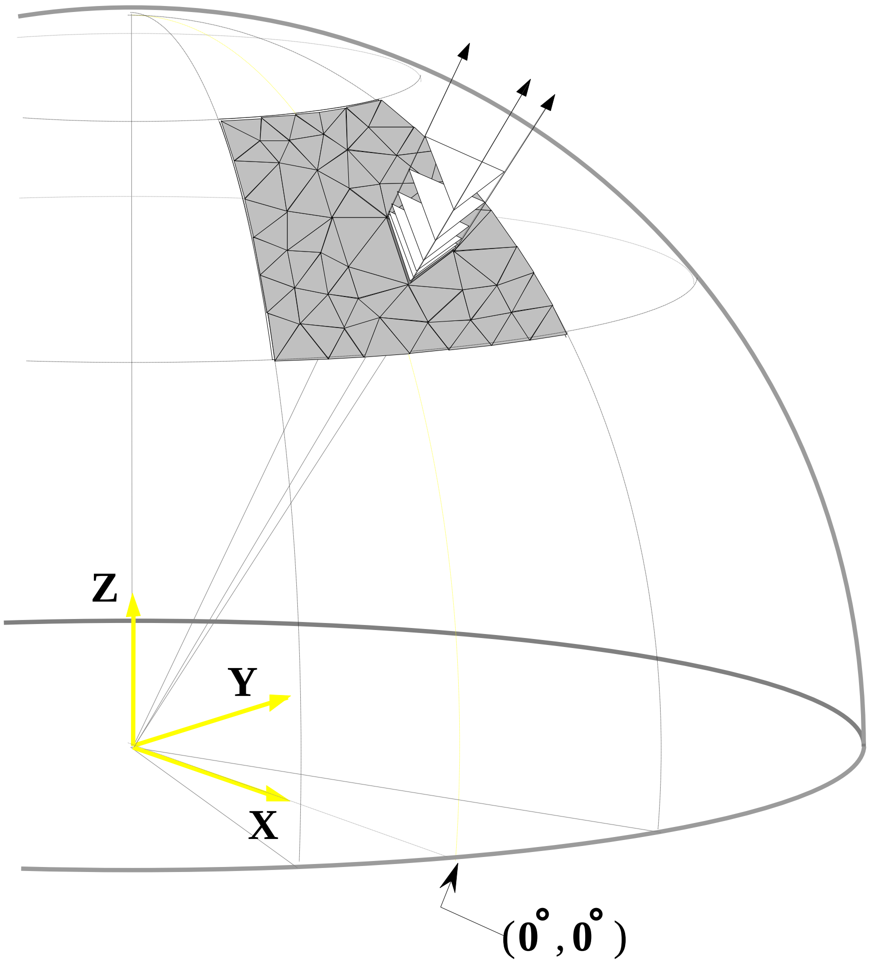
In each small cell or grid, the continuity or conservation calculations become simpler book-keeping calculations of what flows in and what flows out.



Operational Multiscale Environment model with Grid Adaptation

- A new paradigm in NWP
- A merging of state-of-the-art CFD techniques with well-validated atmospheric parameterizations
- Multiscale treatment – implicit up- and down-scale interactions
- Efficient use of large parallel computers
- Complete NWP system

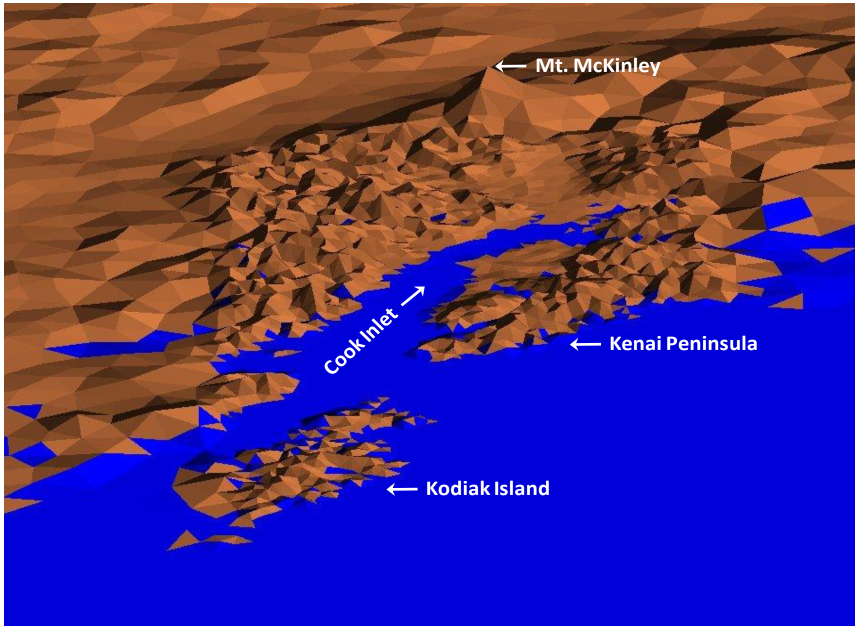
OMEGA Grid Structure



- OMEGA uses a triangular mesh that is unstructured in the horizontal, but structured in the vertical direction.
  - Because triangles can adapt best to surface and atmospheric features, they significantly increase the modeling accuracy.
- The coordinate system is Cartesian with its origin placed at the center of the Earth, the x-axis through the Equator and the prime meridian, and the z-axis through the North Pole.

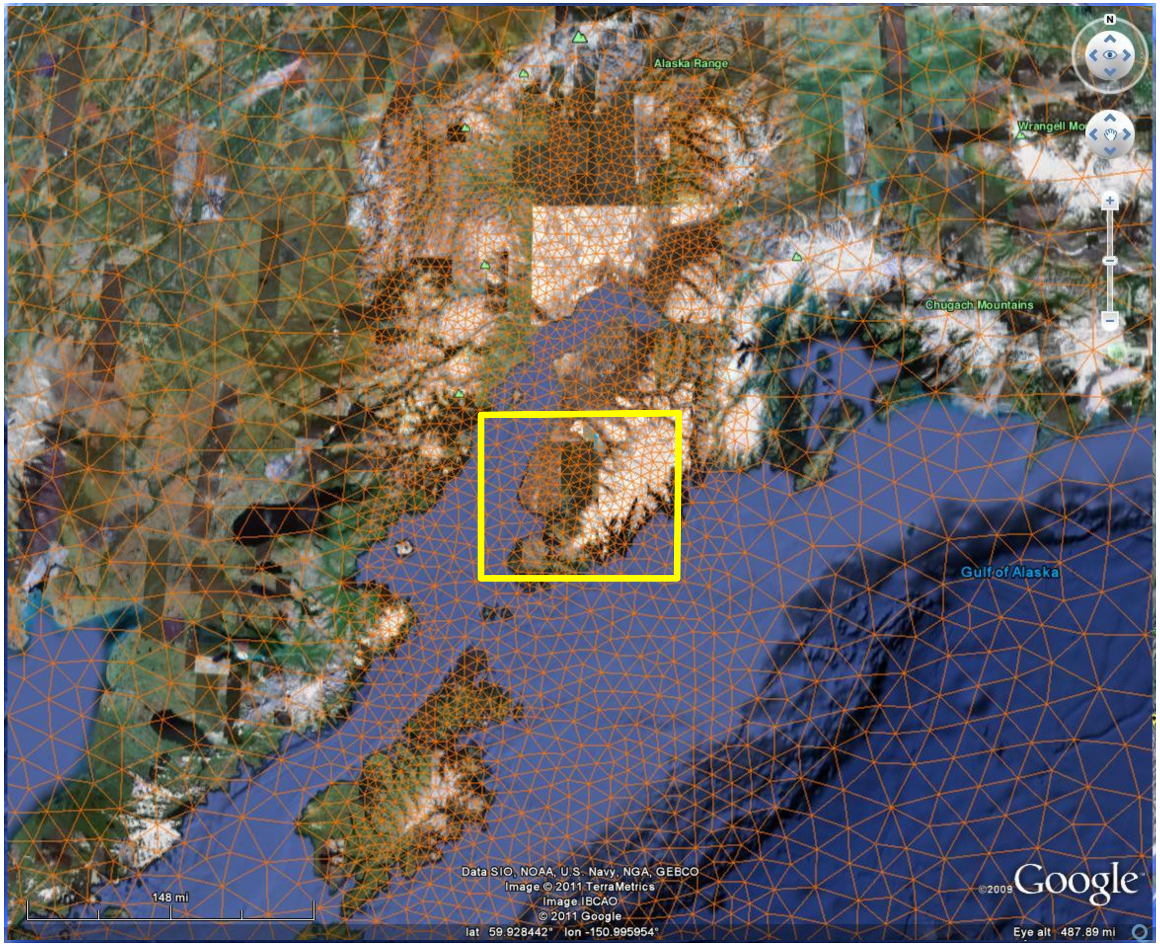
Weather Prediction over Complex Terrain

- Accurate prediction over complex terrain requires the accurate representation of the terrain in the model
- State-of-the-art models such as the Operational Multiscale Environment model with Grid Adaptivity (OMEGA) uses a triangular unstructured mesh to represent the terrain at the best resolution possible under computational constraints



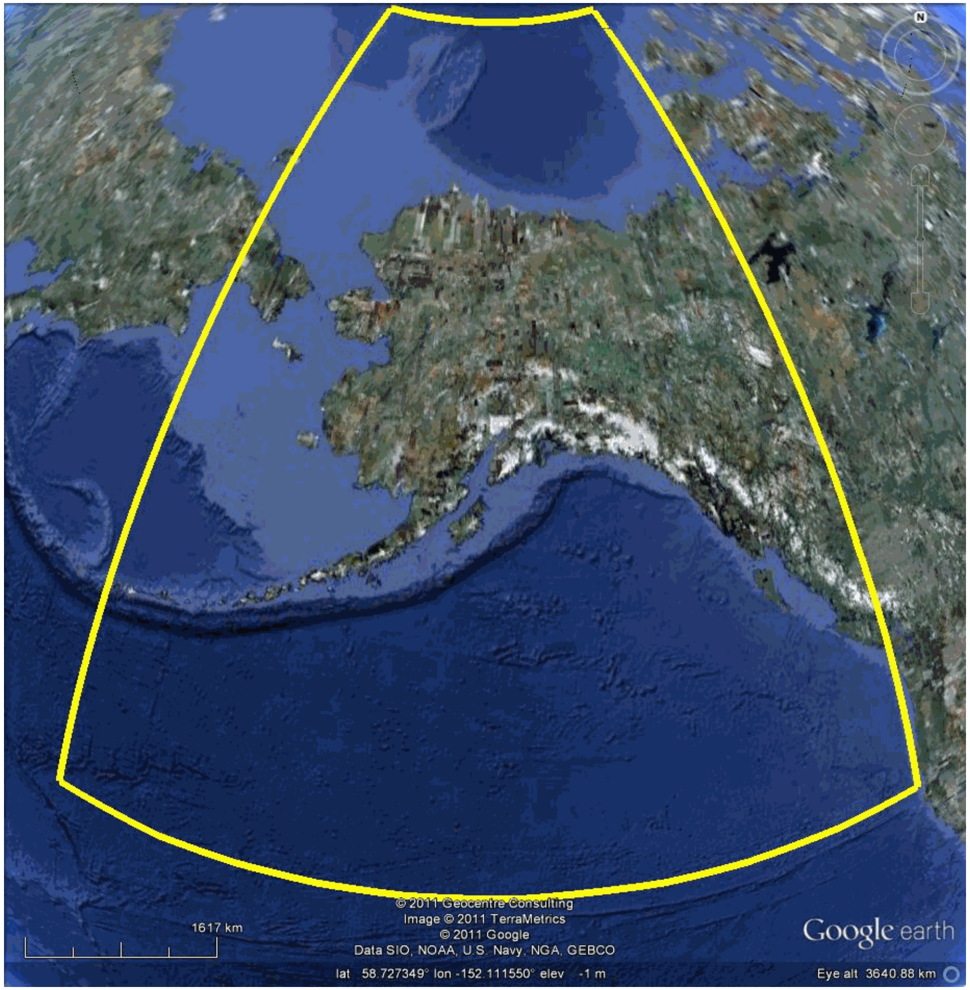
Example
Alaska – Computational Grid

- Resolution:
  - 40 – 60 km background
  - 15 – 40 km intermediate
  - 6 – 15 km finest
- 20,000 cells × 36 layers



Automated Optimized Grid Generation

- OMEGA generates a grid that is optimized to resolve terrain at required resolution
- Triangular grid fits terrain better than traditional rectilinear grids
- Adaptation to
  - Terrain slope
  - Land/water boundaries
  - Other user specified criteria such as specific locations
- Grid can adapt to evolving solution
  - Adaptation to storms such as hurricanes



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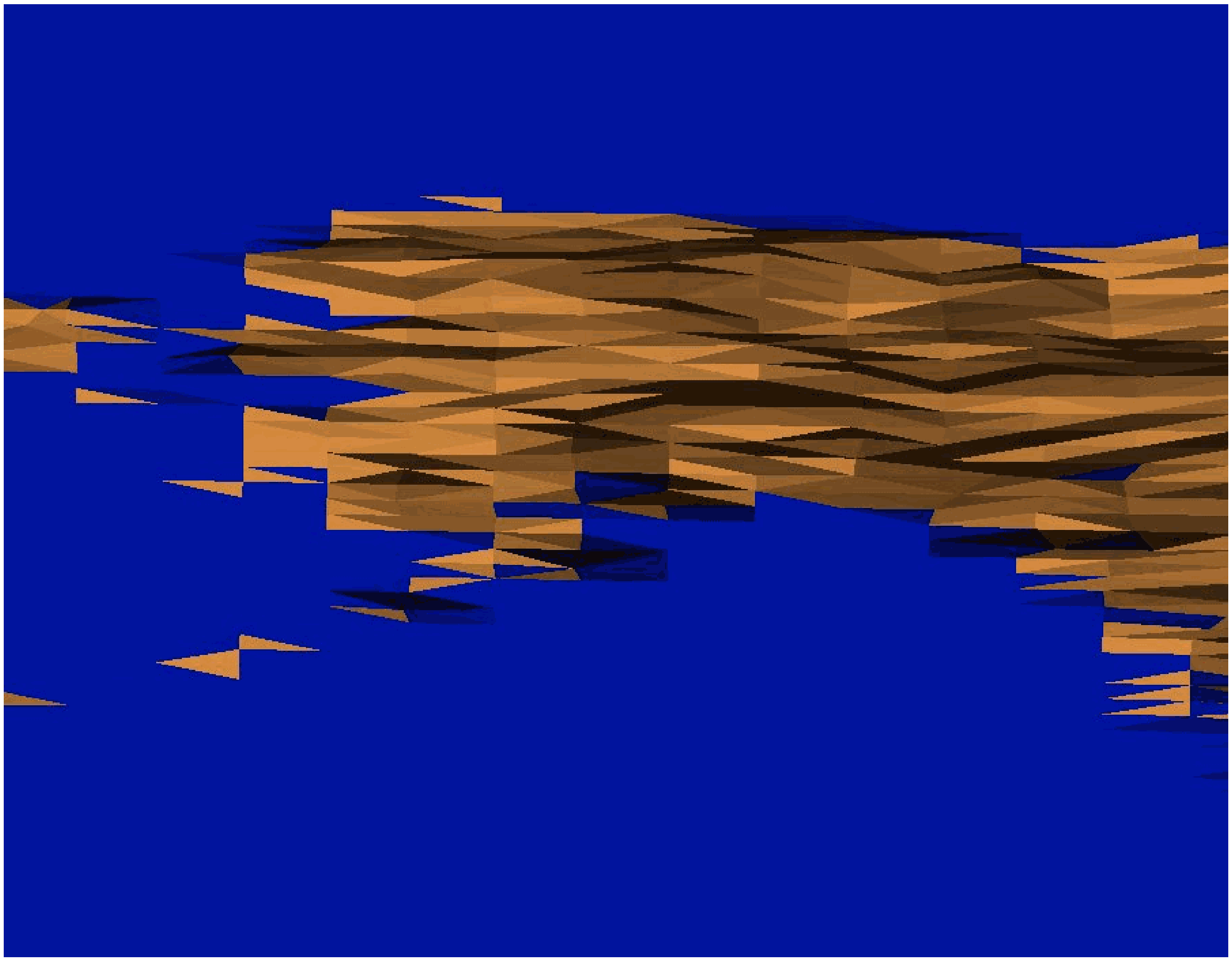
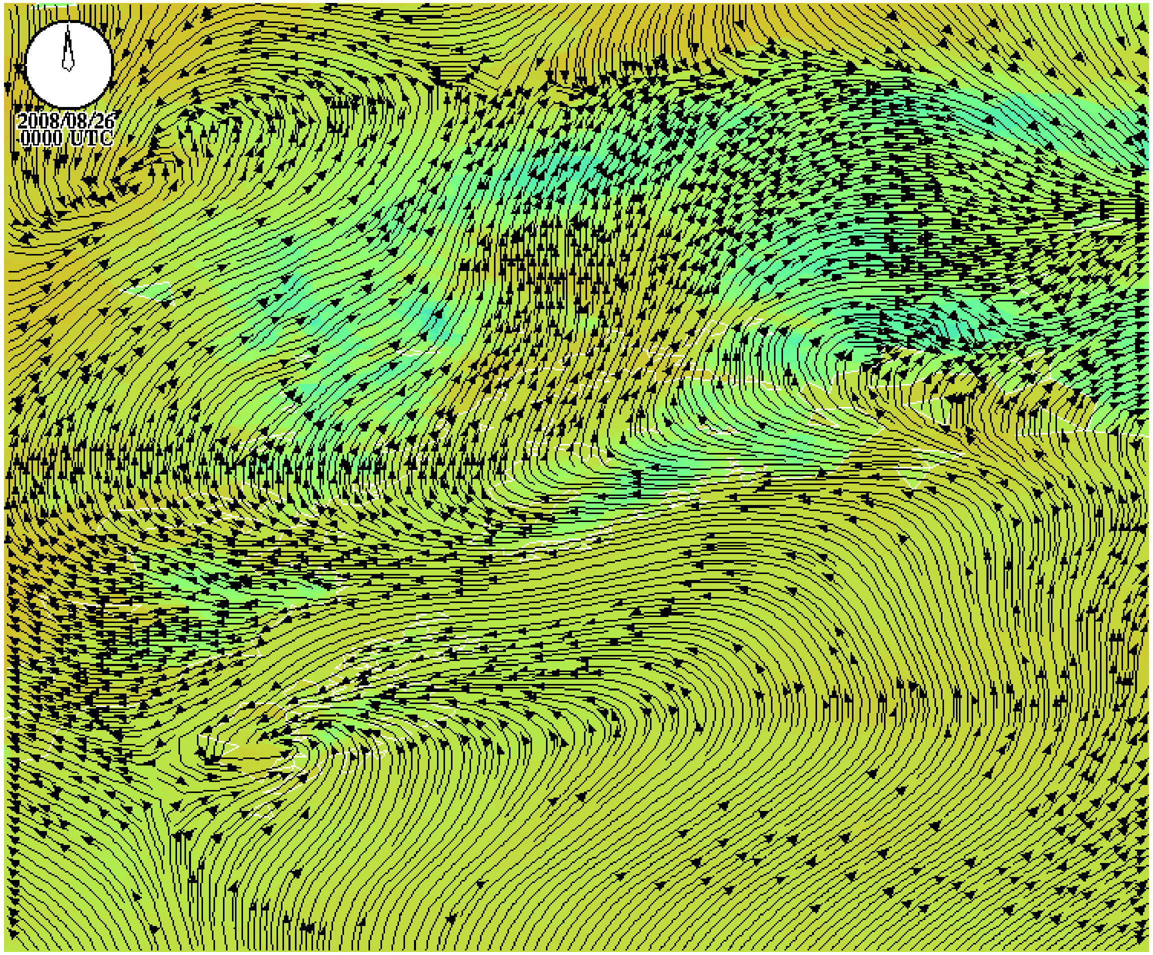
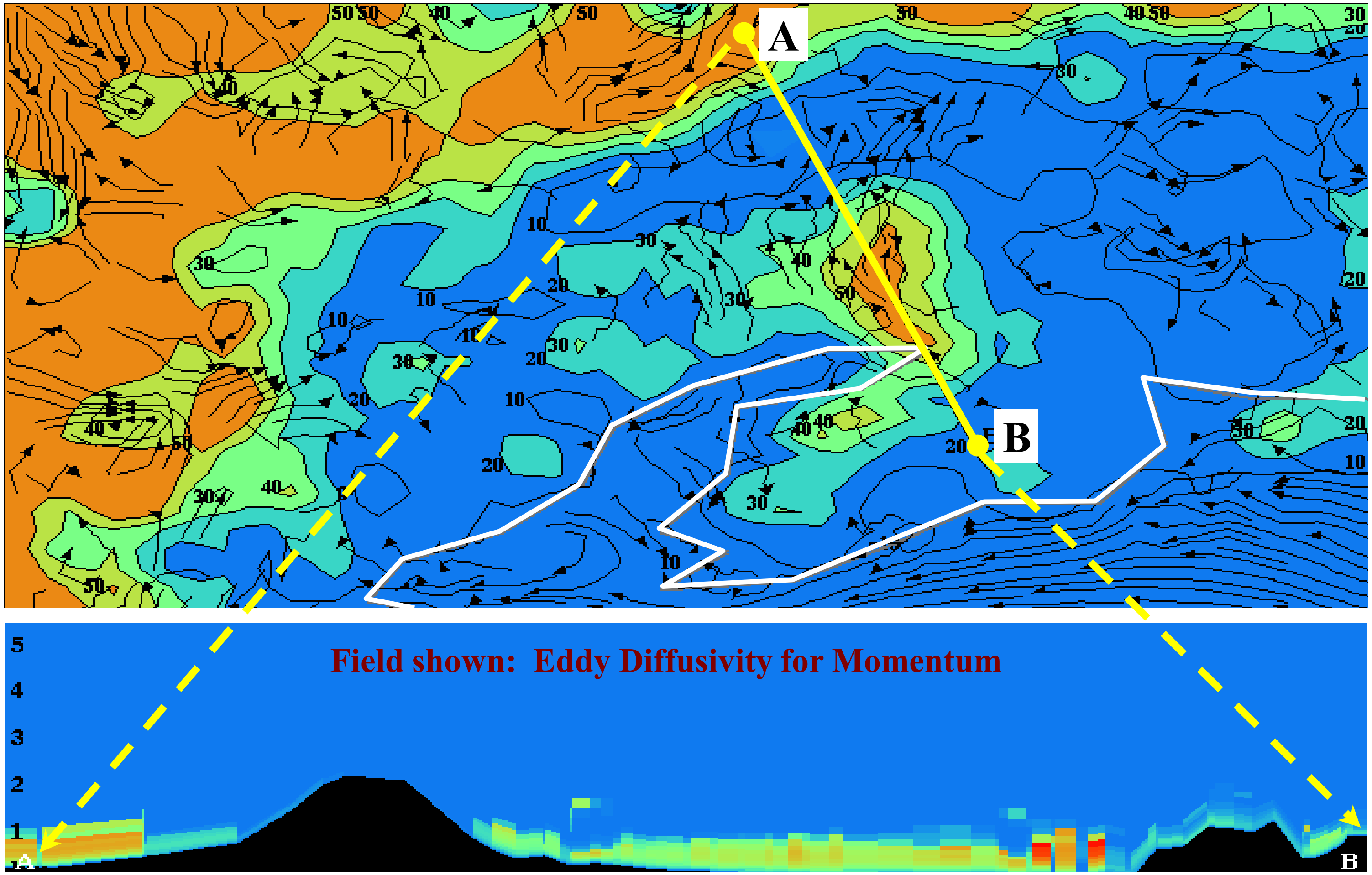
Automated Optimized Grid Generation



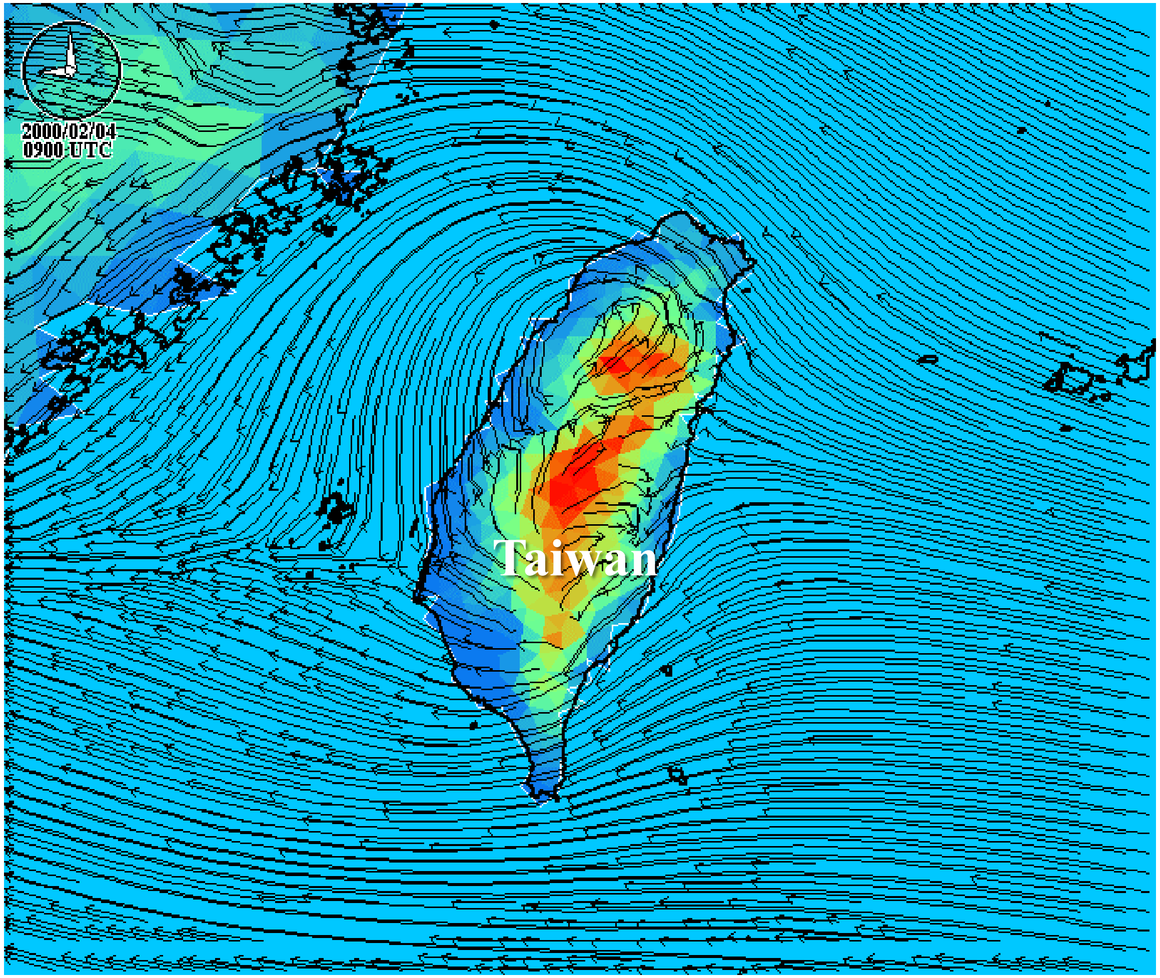
Winds Are Modified by the Terrain



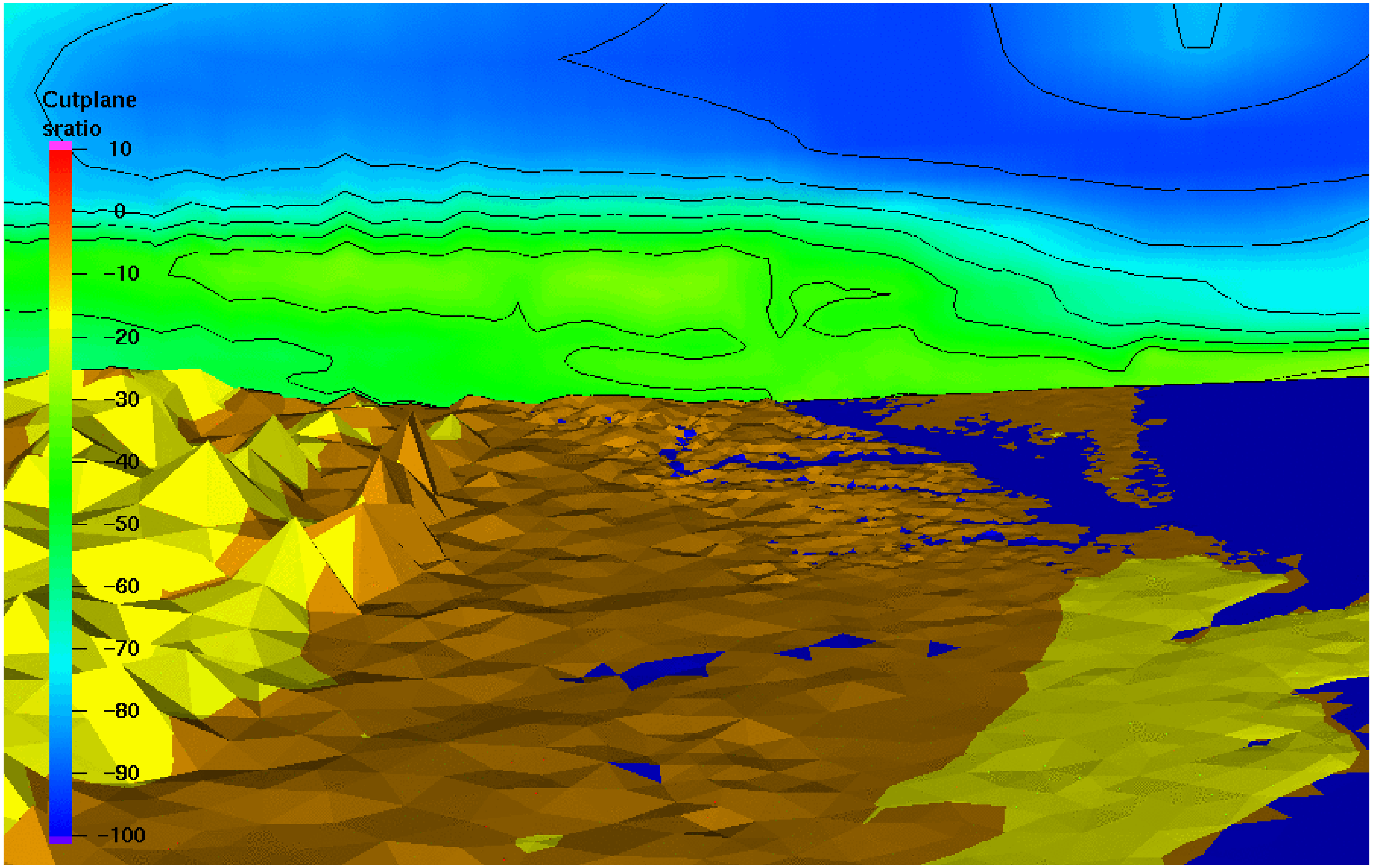
Turbulence Due to Terrain-Induced Shear



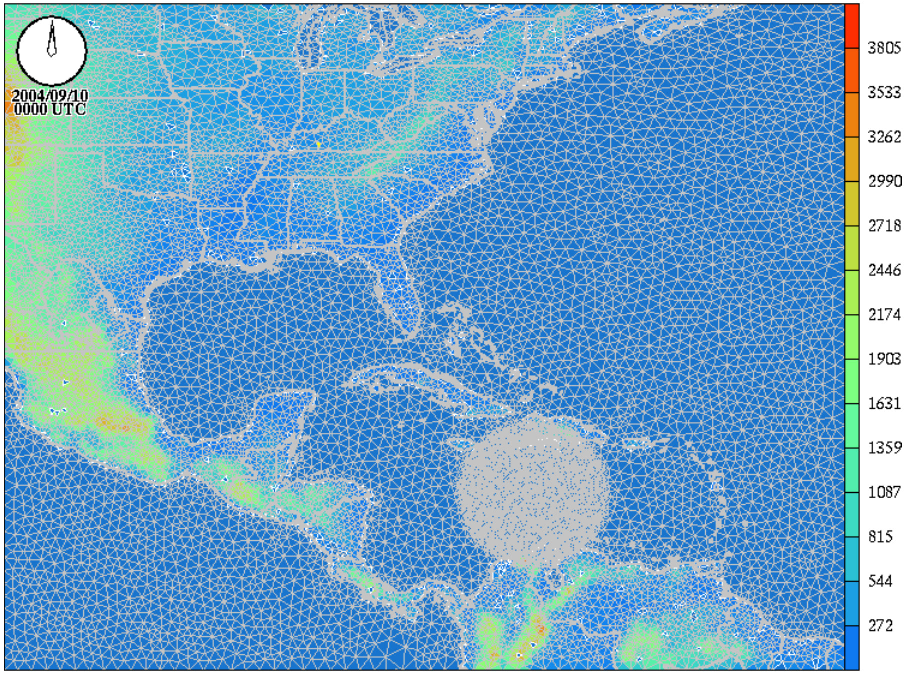
Terrain-Induced Weather (example)



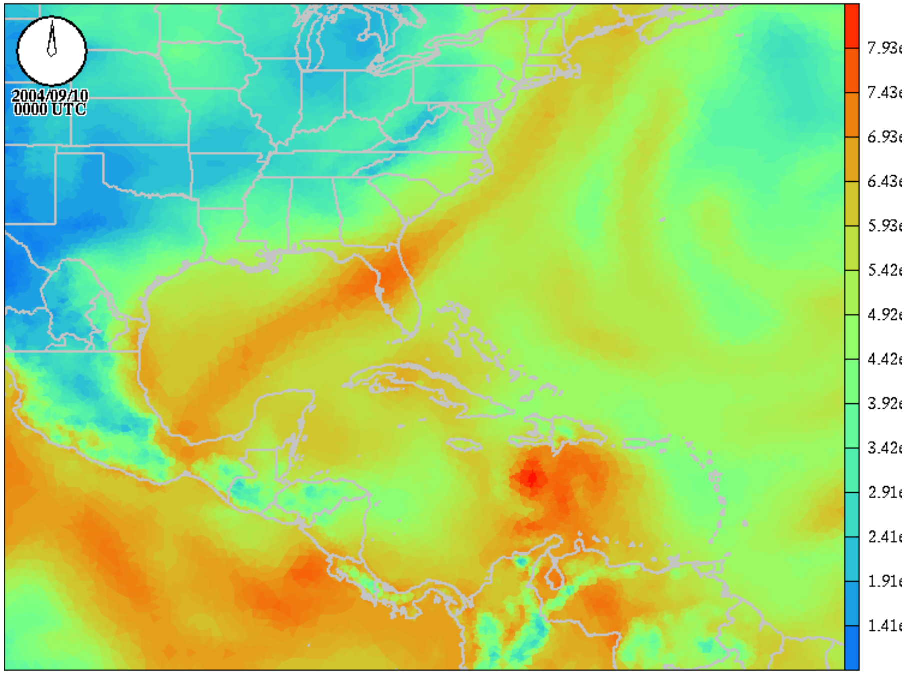
Terrain-Induced Weather (example)



Dynamic Grid Adaptation in OMEGA
Hurricane Ivan – 2004



Dynamic Grid Adaptation – Hurricane Ivan



4 Days Forecast – Case: Hurricane IVAN – Column Integrated Vapor (m)
Using Dynamic Grid Adaptation

Grid resolution ranges from 100km down to 1km, dynamically adapting to the hurricane location

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Airship Routing – Optimization for Weather

Routing Issues

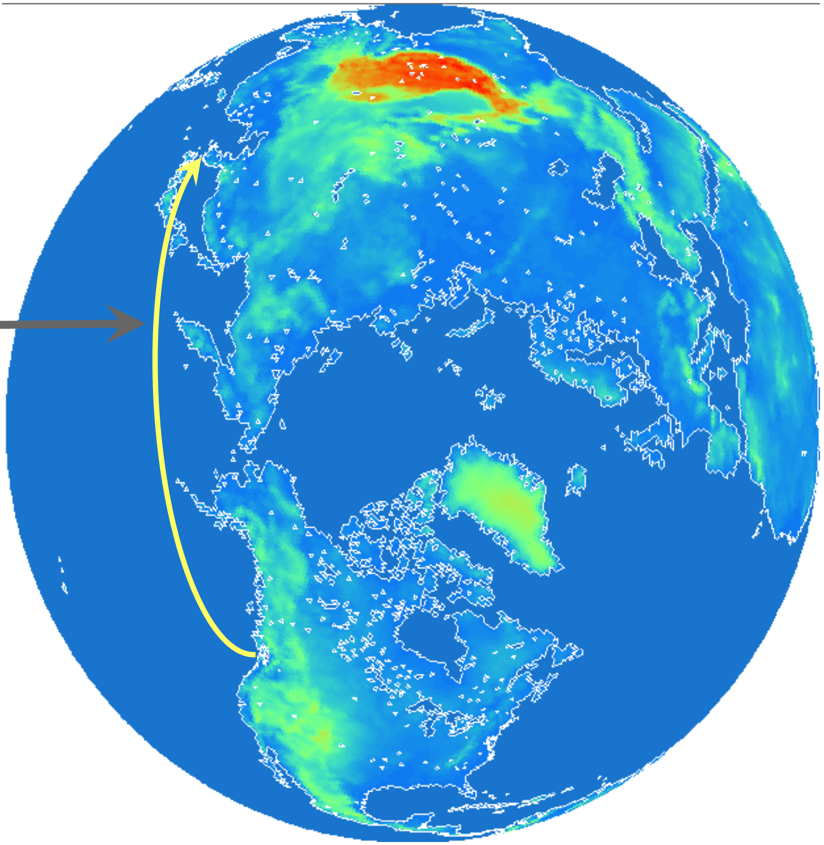
- Most airships fly in the lower troposphere in which winds and other weather elements change rapidly due to terrain, land-cover and other factors
- Airships are expected to operate in remote and sparse infrastructure regions
- Need to carry as much fuel as possible
- Fuel vs. payload (cargo) tradeoff
- Long transits increase the possibility of encountering adverse weather
- This apparently simple problem of avoiding adverse weather is made complex as the weather evolves during the flight

Routing Methodology

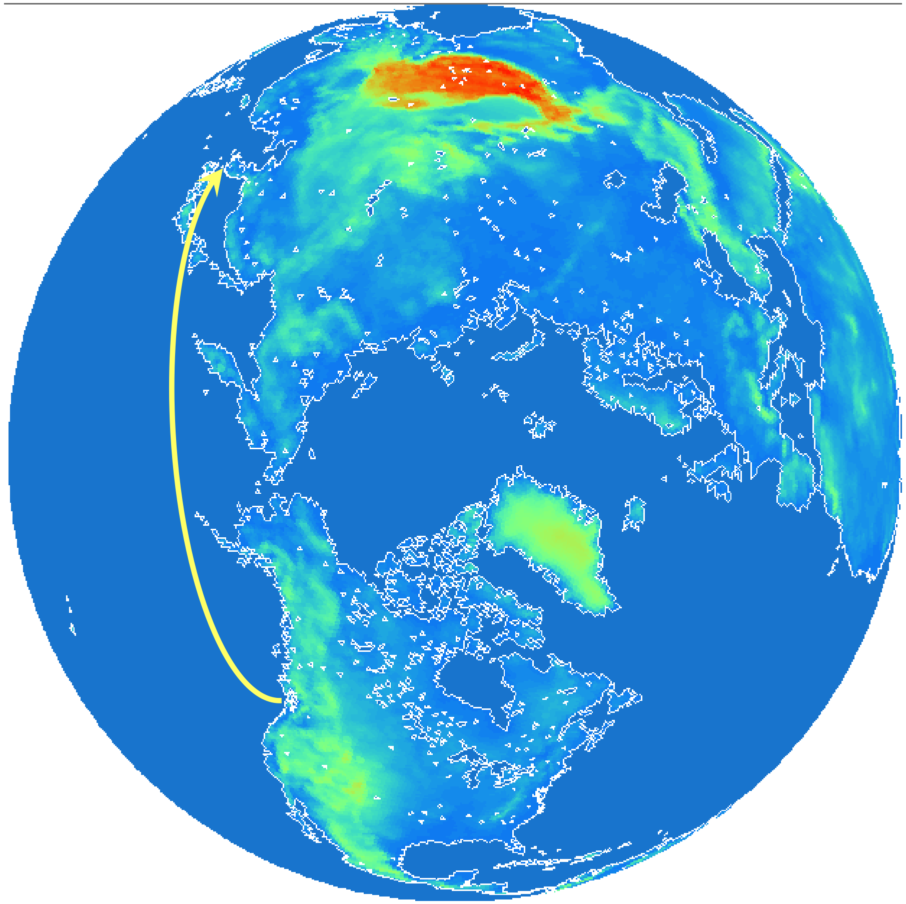
- Avoid adverse weather events
    - Storms, head winds, precipitation events
- Avoid terrain
- Find tail winds if possible
- Use detailed weather forecasts that include effects of terrain

Airship Route Optimization for Weather

- Large cargo airships – range vs. payload considerations
- Default best route (no weather) – Great Circle Route (minimal distance at the same altitude)
- Change route to move away from “bad” weather (e.g., head winds and storms) and to take advantage of “good” weather (e.g., tail winds)
- As an example a trans-Pacific route between Ft. Lewis, Wash., and Pusan, South Korea is considered

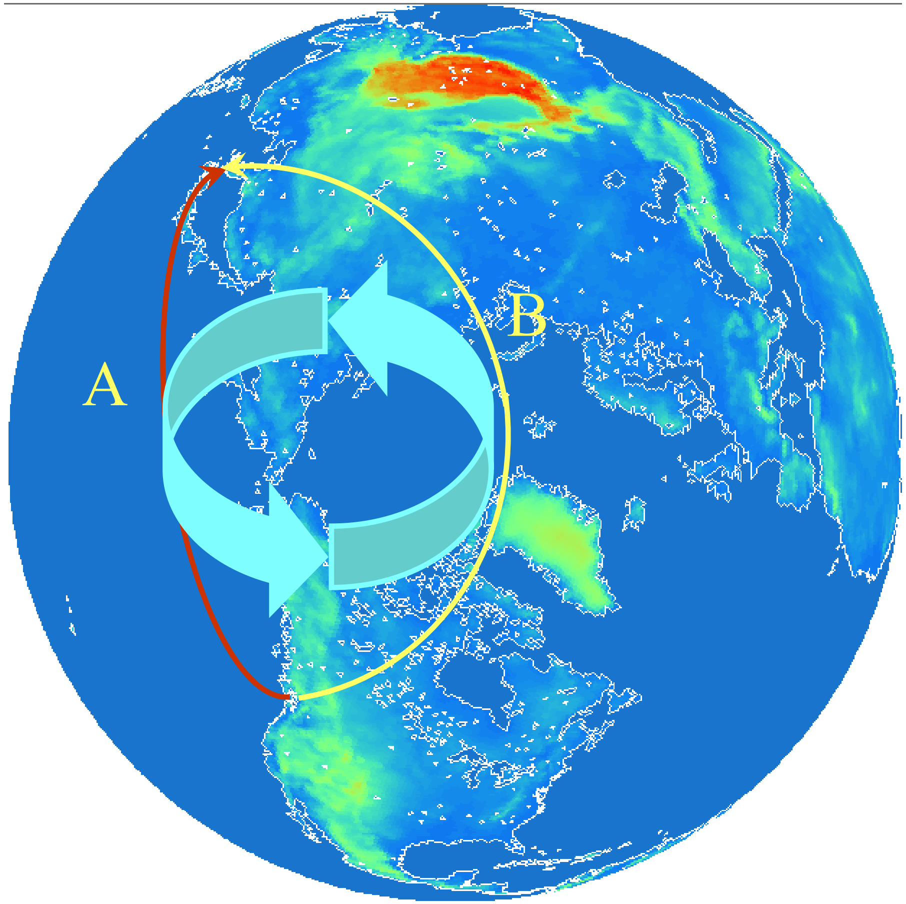


Great Circle Route



- Minimum distance
- V_{ground} reduced by:
  - Headwind
  - Crab required to counter crosswind

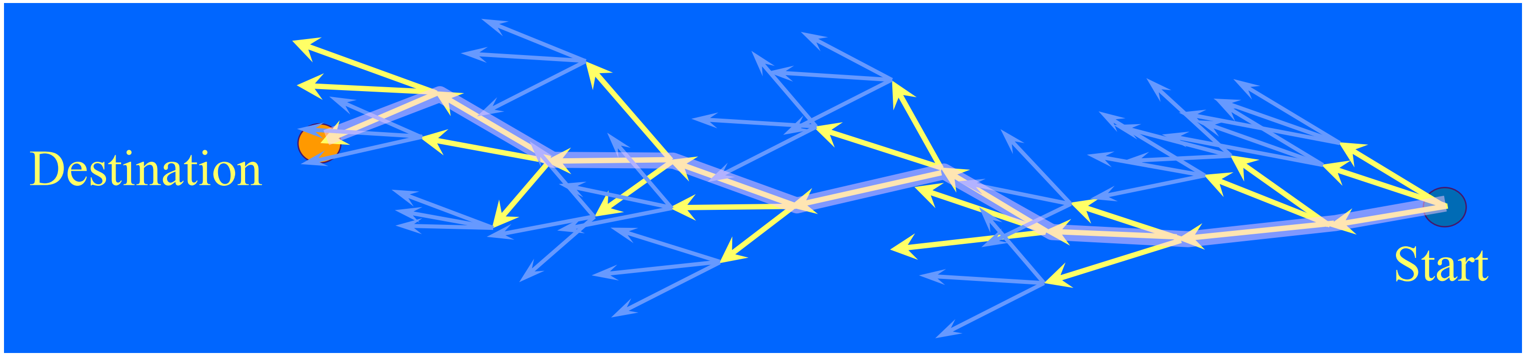
Minimum Time Route



- Travel around a large weather system (40 kt average winds)
- TAS 80 kts
- Assume distance increases by 50 percent (Route A vs. B)
- Assume 40 kt headwind
- Great Circle Time: D/V
- Path A Time: 2 D/V
  (= D/(0.5 V))
- Path B Time: D/V
  (= (1.5 D)/(1.5 V))

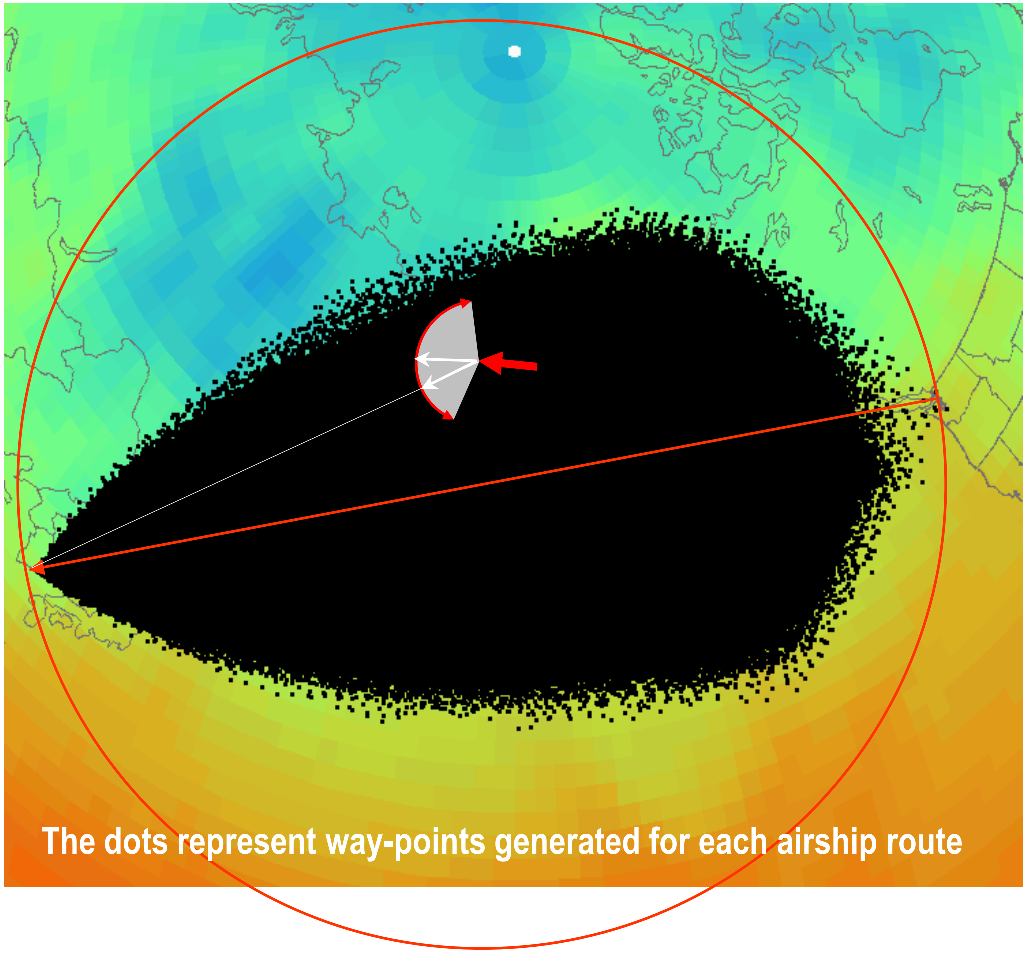
Route Optimization Algorithm

- Uses the Great Circle Route as a benchmark
- A Monte Carlo analysis approach is used by breaking the route into multiple short flight segments
- Each segment is tested against the performance metric
- Only the best segment is retained in each step
- Recursive definition of routes
- Branching is constrained by other factors such as nearness to the destination and current direction of travel

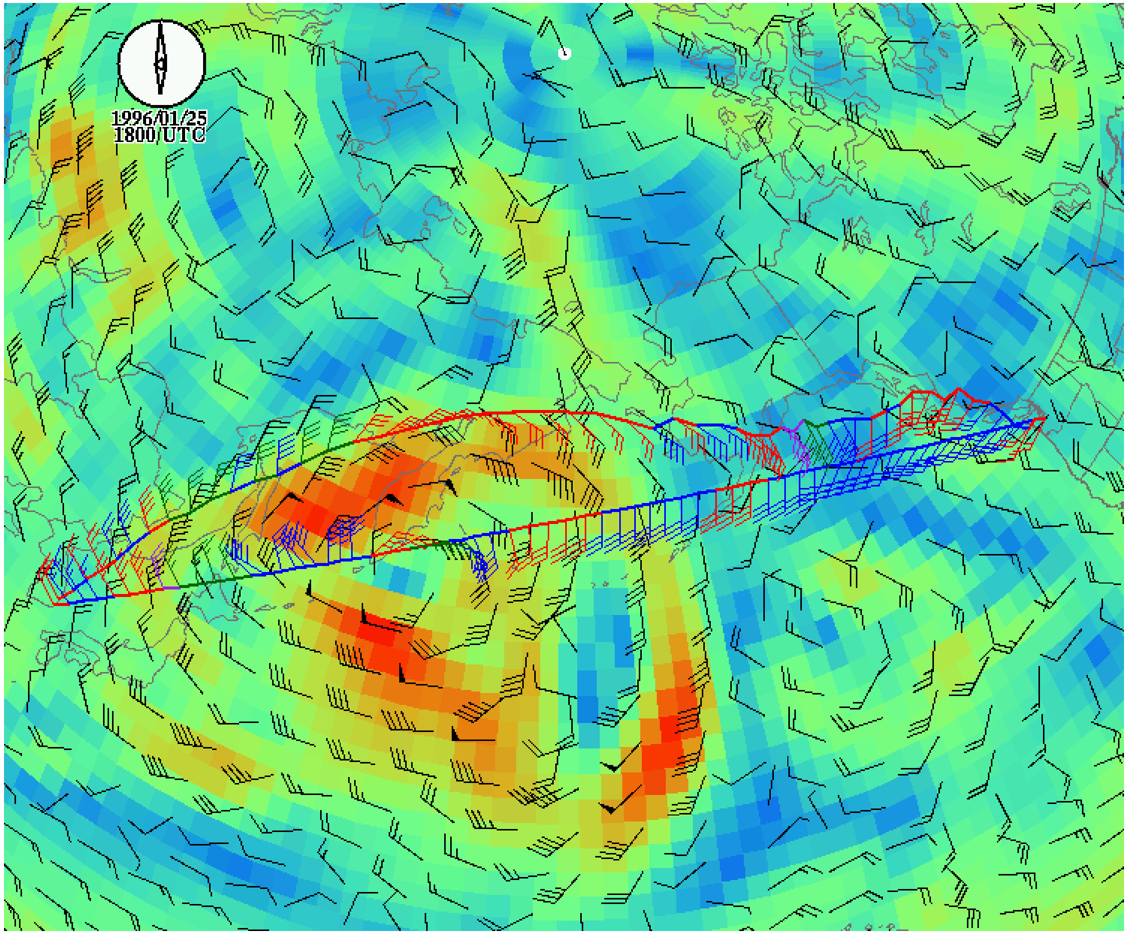


Algorithm Constraints

- Around 1 million routes are sampled per run
- Routes are restricted to a circular region with the Great Circle Route as its diameter
- Routes are constrained within a pre-determined angular sector
- The new routes are weighted by the previous heading
- The new routes are also weighted by the heading towards the final destination



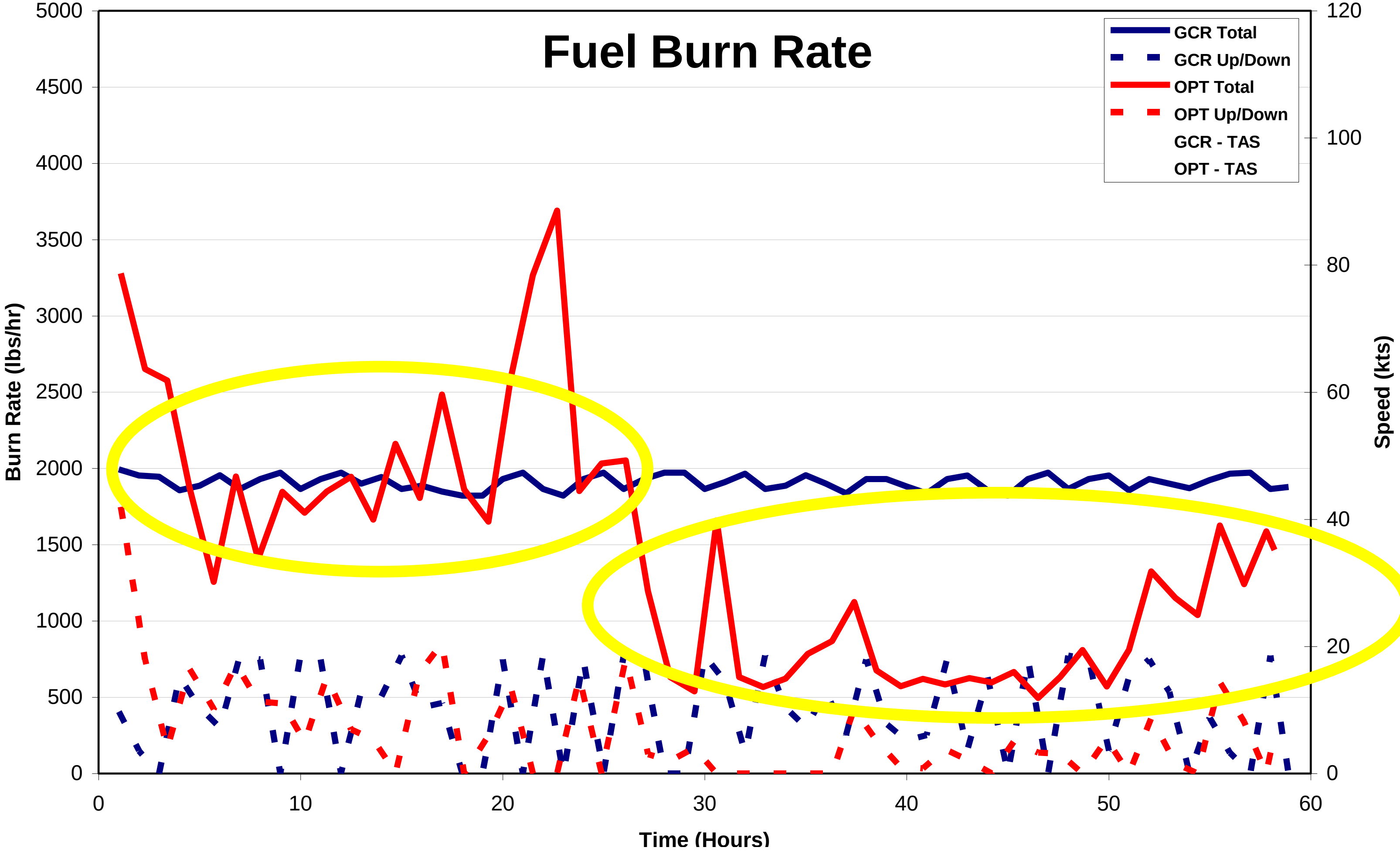
Optimal Route with Altitude Changes



- As the airship proceeds, the “best” altitude is chosen for each hop
- Altitudes are constrained between an upper (2500 m MSL) and lower bound (1000 m MSL)
- Hops every hour with two tracks spawned with each hop
- Route segments are checked against terrain
- GCR: 8421 km; 66.32 hrs
- Optimal: 9013 km; 53.60 hrs

Optimization Using Ground Speed

Ft. Lewis to Pusan



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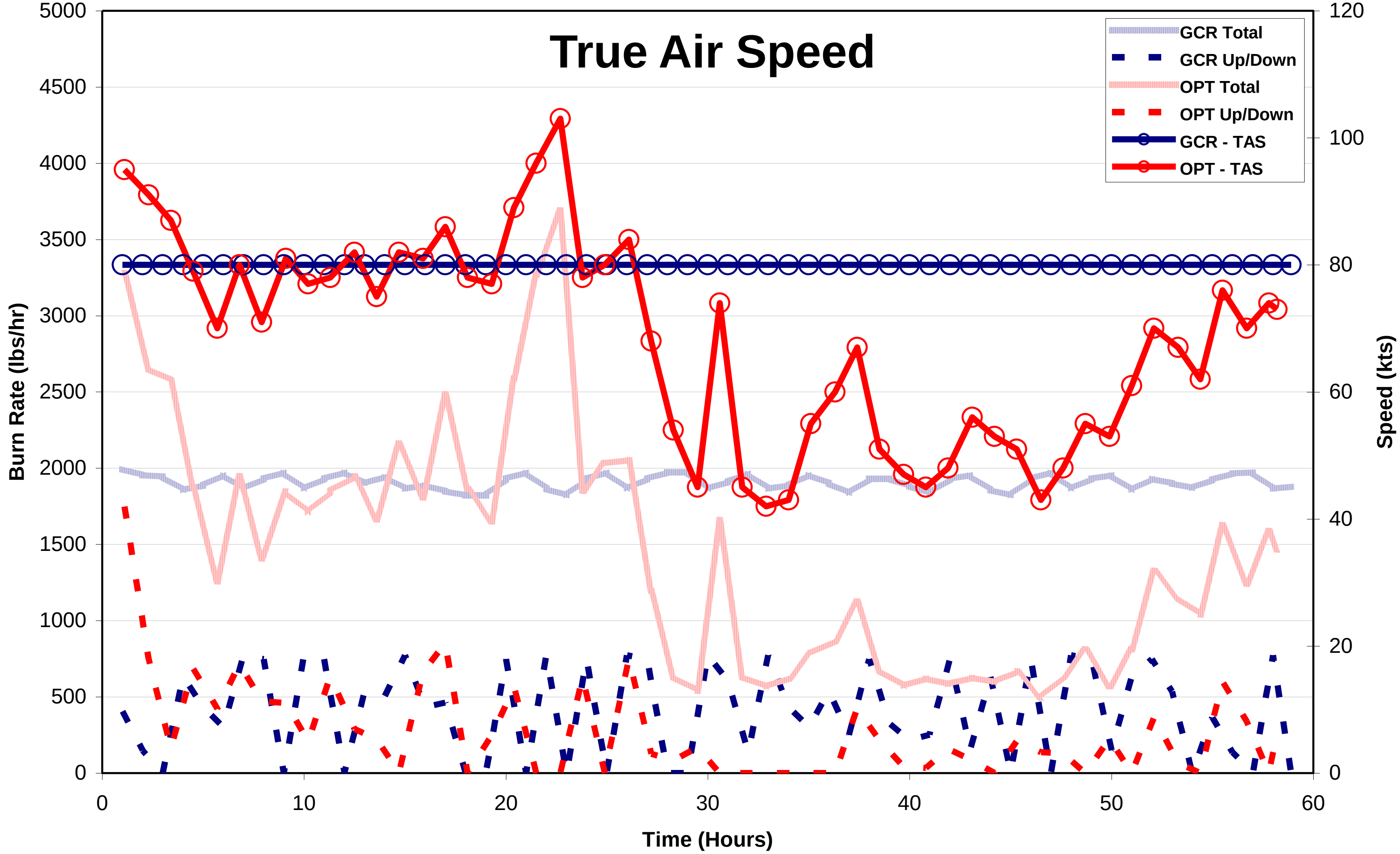
Optimization Using Ground Speed

Ft. Lewis to Pusan



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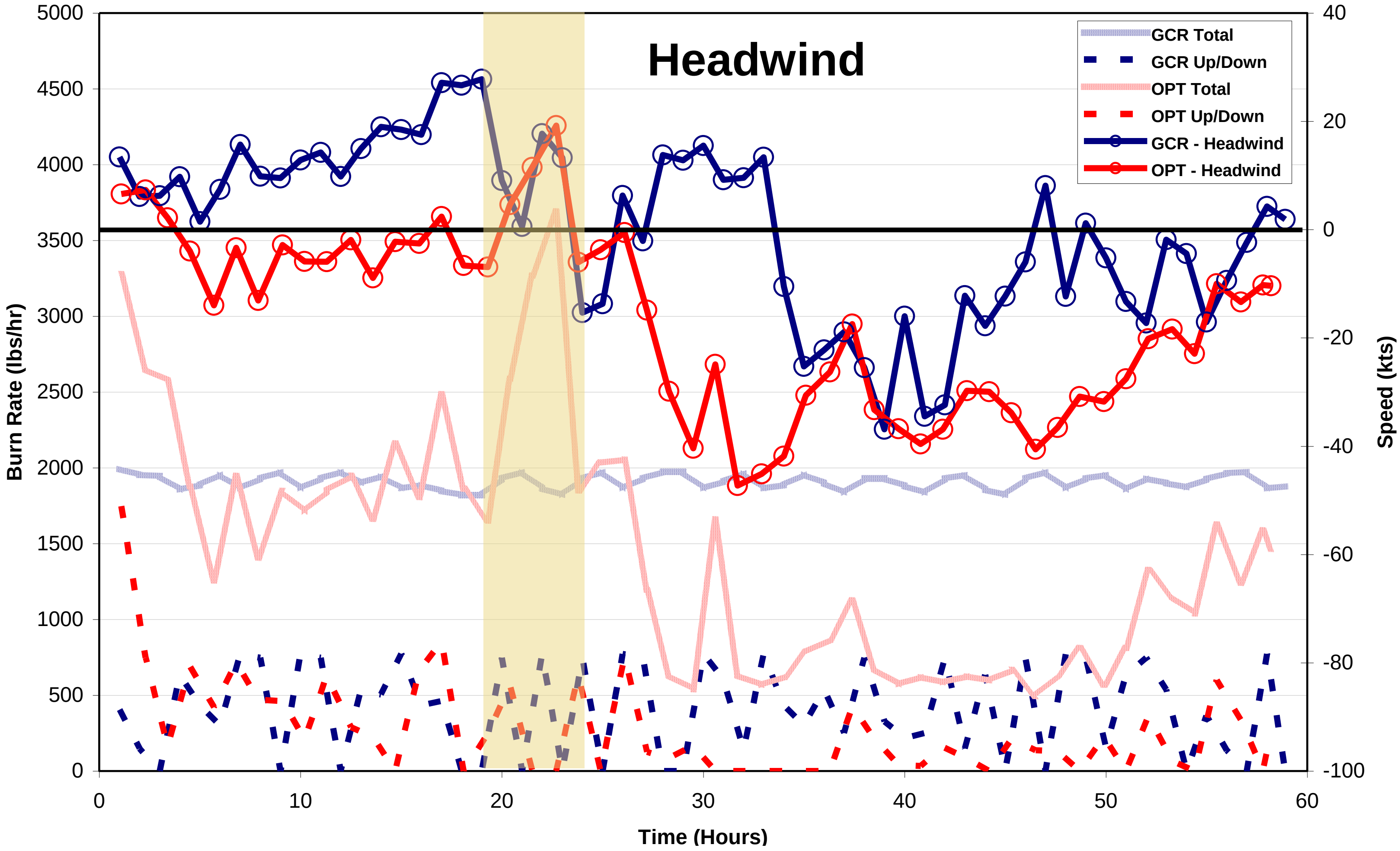
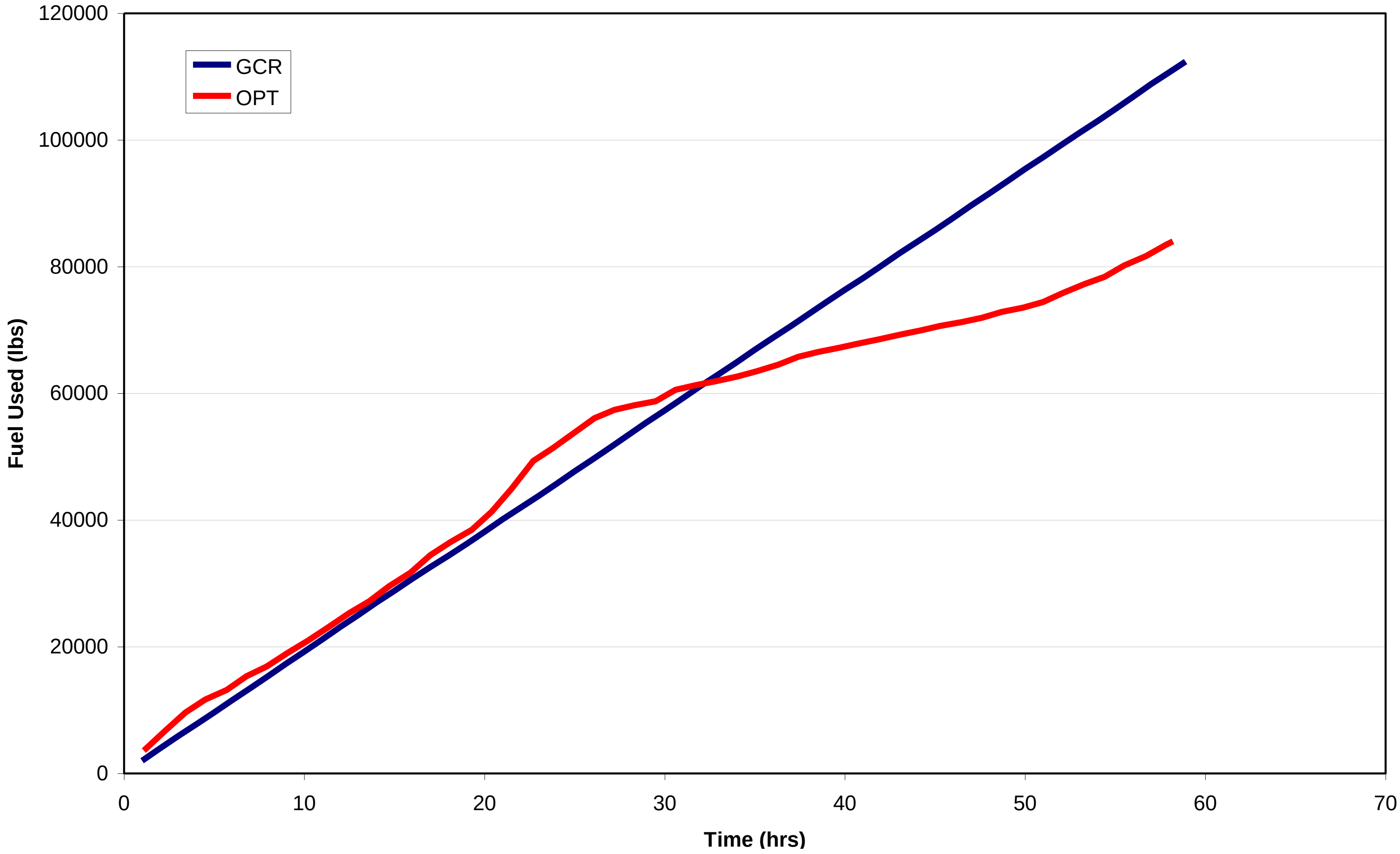
Optimization Using Ground Speed

Ft. Lewis to Pusan

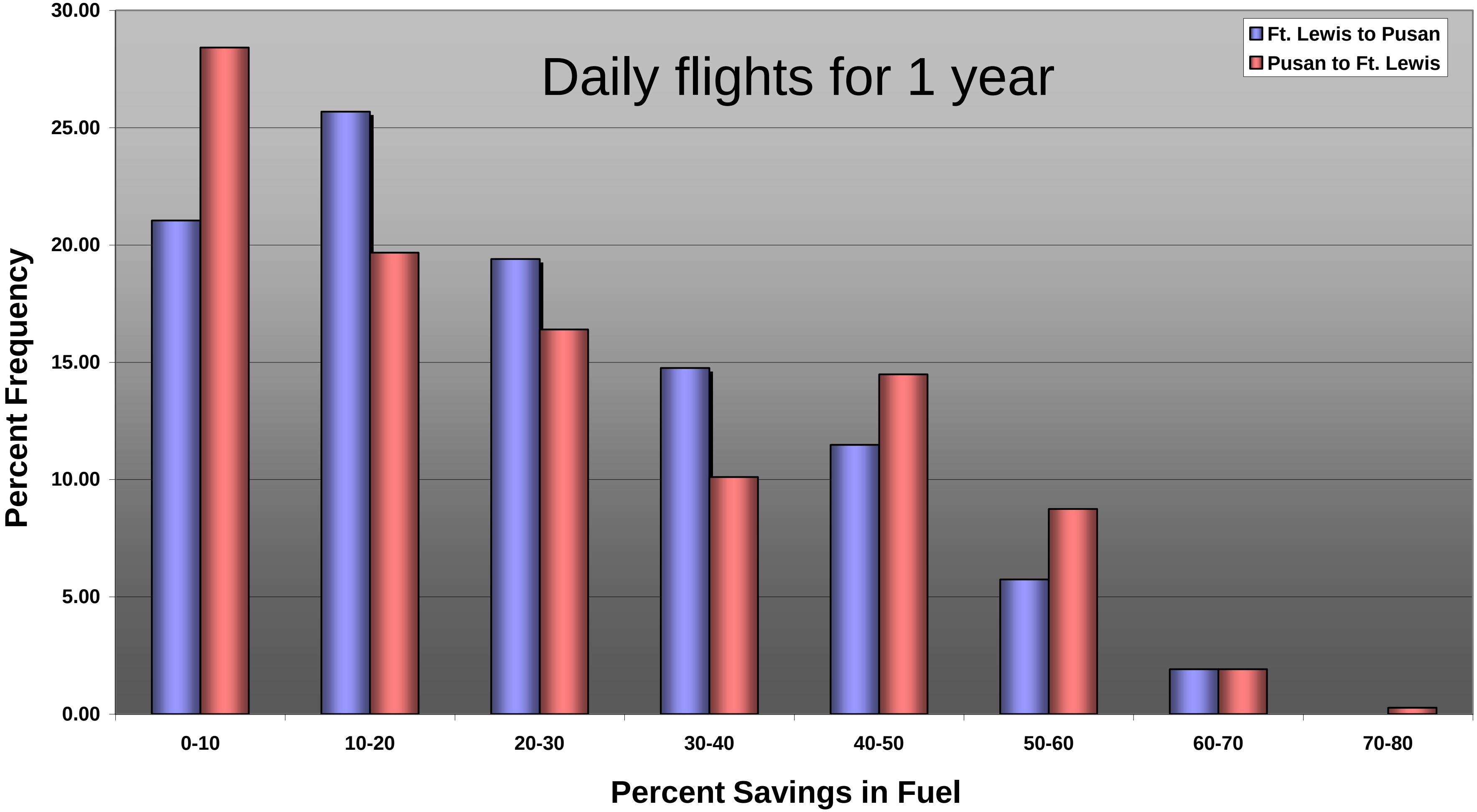


Optimization Using Ground Speed

Ft. Lewis to Pusan



Long-Term Performance



Benefits

- Operational risks due to adverse weather can be significantly reduced
- Substantial fuel savings are possible over long transits
- Airship utility rate is increased – less exposed to adverse weather
- Adequate margins of airship flight safety can be maintained without reliance on pilot guess work
- Planned flight arrival times are less susceptible to disruption from adverse weather
- Fuel and payload weight can be optimized due to known fuel consumption en route
- Greater weatherability might reduce insurance premium costs

Summary

- Airships are vulnerable to weather
- Airship operations require an accurate knowledge of weather
- A new paradigm in numerical weather prediction
  - Unstructured adaptive grid
- Accurate representation of terrain facilitates accurate prediction of terrain-induced circulations
- Dynamic grid adaptation enables the focusing of computer resources where they are most needed
- Route optimization using weather model output shows a great potential for fuel savings for large cargo airships as well as improving operational safety
- Savings possible for normal aircraft – not so dramatic as airships
- Better optimization methods?

For further information, contact …

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