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The Structure and Dynamics of Columbia Gorge Gap Flow Revealed by High-Resolution Numerical Modeling

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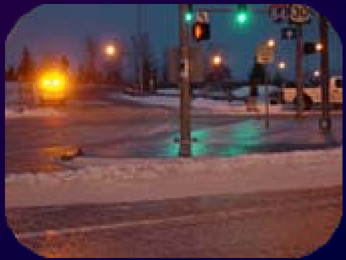
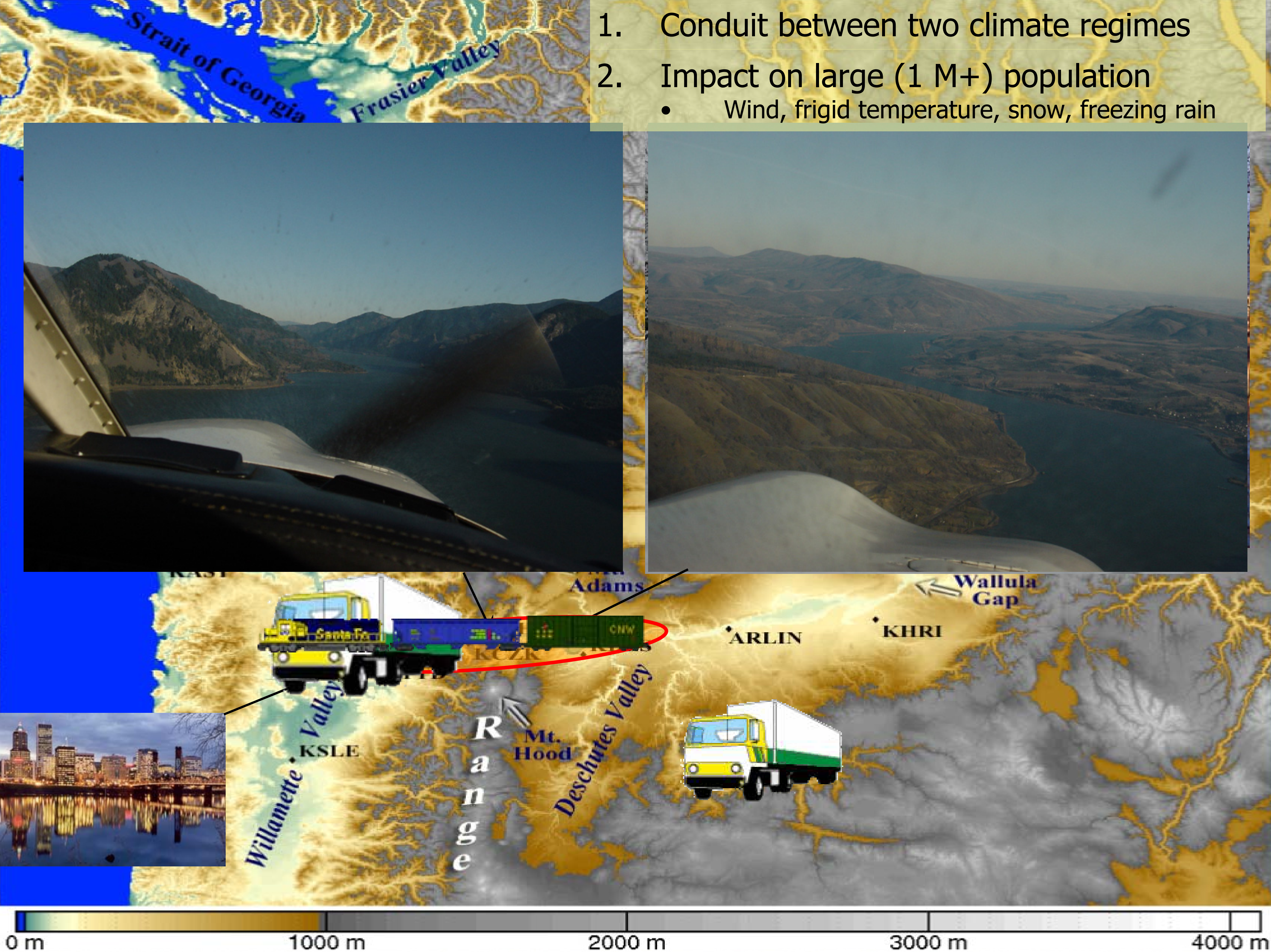


Northwest Weather Workshop. March 4-5, 2005

The Columbia Gorge

A Natural Laboratory

1. Conduit between two climate regimes
2. Impact on large (1 M+) population
   - Wind, frigid temperature, snow, freezing rain



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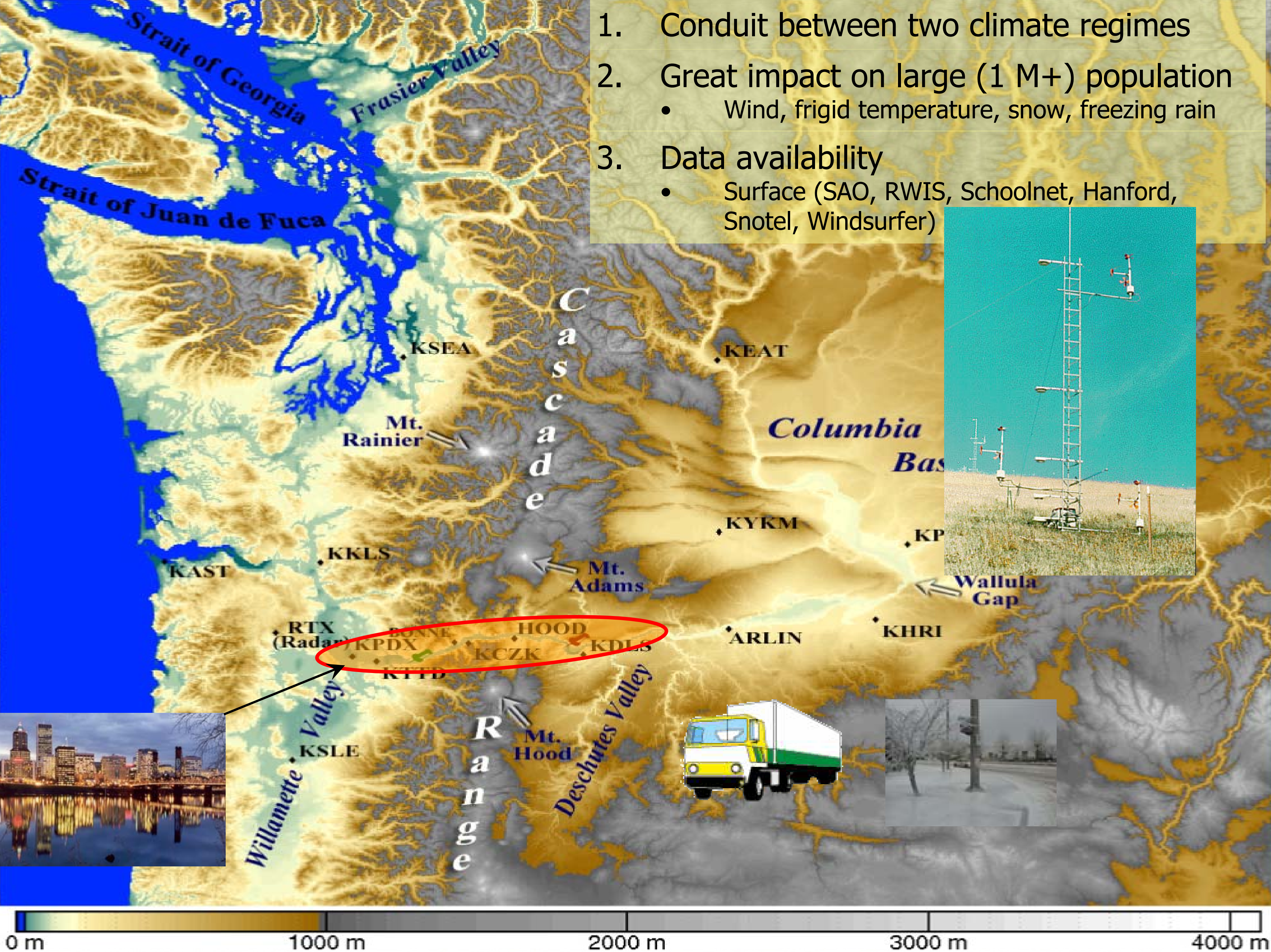
2. Great impact on large (1 M+) population
   - Wind, frigid temperature, snow, freezing rain
3. Data availability
   - Surface (SAO, RWIS, Schoolnet, Hanford, Snotel, Windsurfer)



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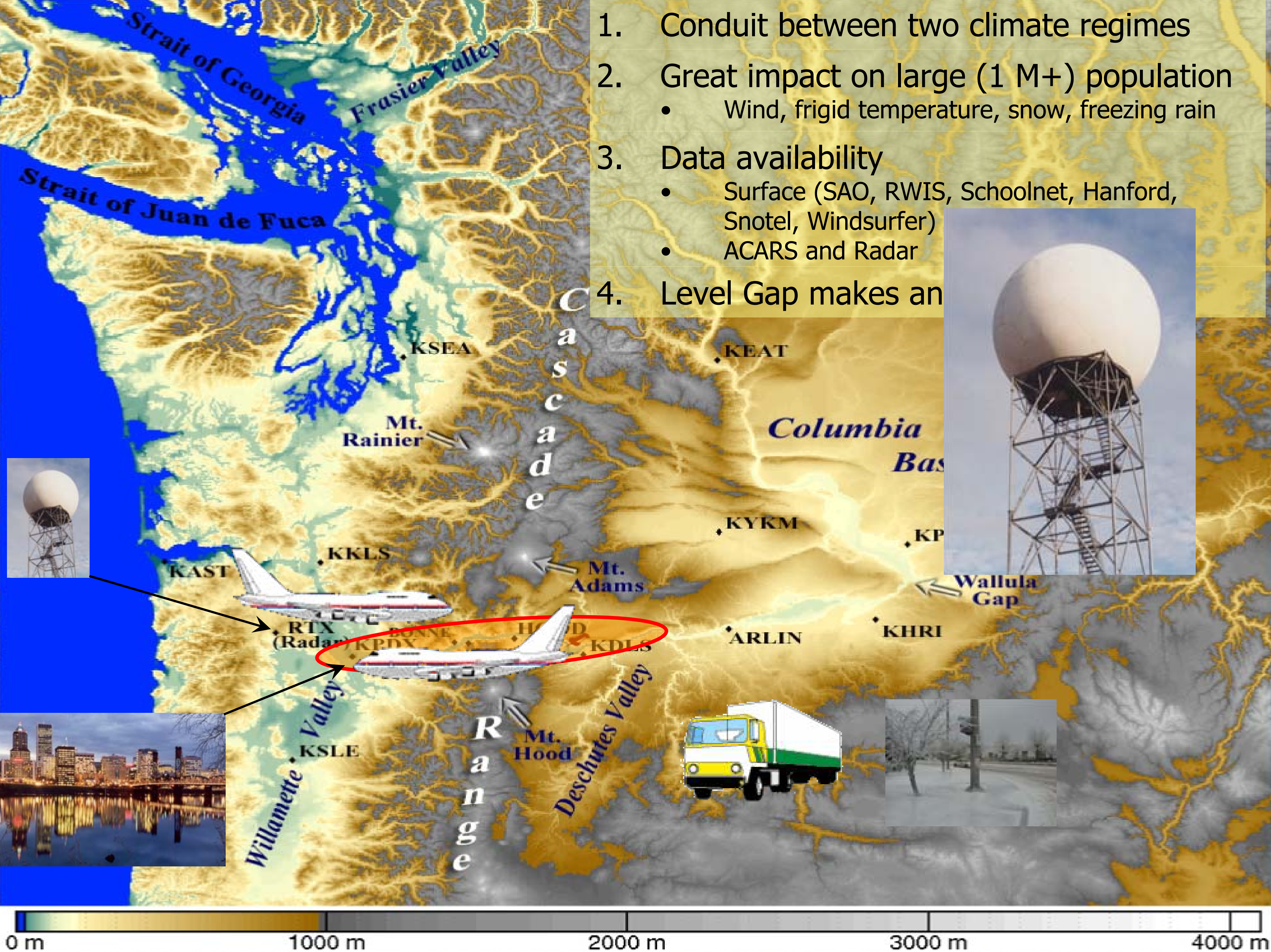
2. Great impact on large (1 M+) population
   - Wind, frigid temperature, snow, freezing rain
3. Data availability
   - Surface (SAO, RWIS, Schoolnet, Hanford, Snotel, Windsurfer)
   - ACARS and Radar
4. Level Gap makes an



Research Objectives

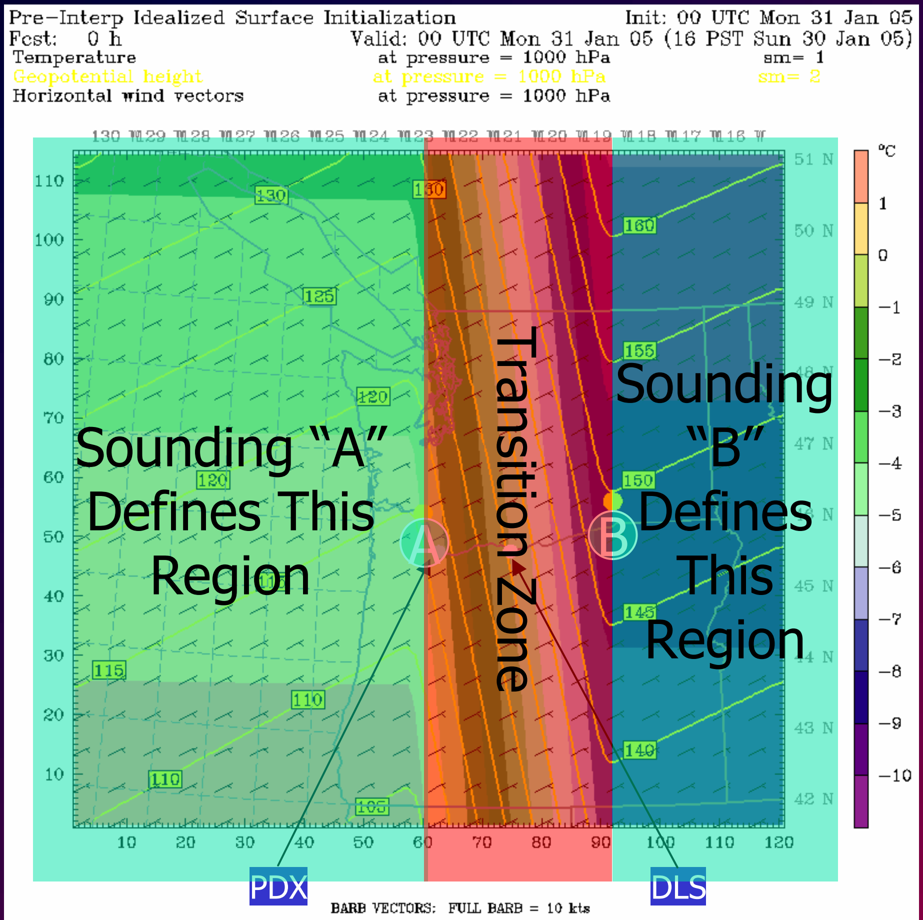
1. Better understand gap winds in a level gap
   - Describe the 3-D structural characteristics and determine the dynamical mechanisms that are responsible
   - Achieved through:
     - Case studies of real events (observations/modeling)
     - **Idealized simulations**
2. Establish the usefulness of NWP for simulating a complex topographic features such the Columbia Gorge
   - Determine the model resolution and configuration required
   - The answers will help define future decisions for operational models (important since gaps are common)
3. (1) + (2) = Better Forecasts

Studying a Broad Phase Space

- Observational and modeling of Dec 2000 Gorge flow event
  - This study and the work of other researchers suggested that the gap flow behavior was analogous to hydraulic flow through a channel containing width variations
    - How well does this analogy hold up to closer scrutiny?
    - Does it work about other scenarios?
- More case studies?
  - Difficult to evaluate synoptic influence
  - Impossible to isolate the effects of specific differences in upstream conditions
  - Limited sampling capability
- Create idealized simulations
  - Ability to explore a range of specific upstream conditions in a systematic fashion (e.g. stability profile, wind shear, initial ΔT)
  - Synoptic influence is known and controllable

Initialization Method

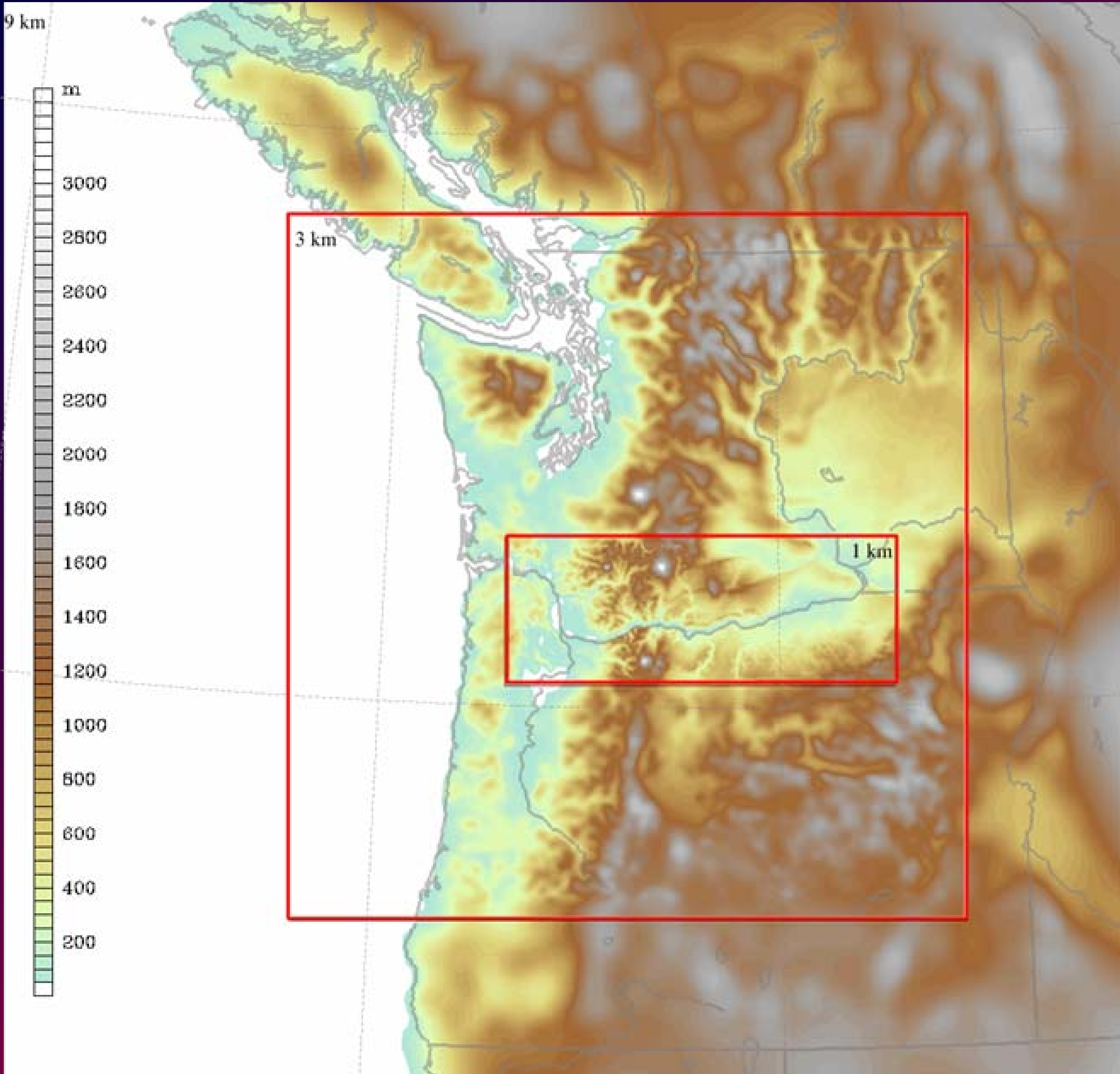
- Create two virtual "soundings" based upon desired regime



- Specify temperature and (optionally) RH on pressure levels and also SLP
- Wind is specified on pressure levels and is constant on each level
- T, Z and SLP can then be derived everywhere by assuming thermal wind balance
- Transition Zone:
  - Linearly interpolate T and RH
  - Then calculate Z, P hydrostatically
- Create constant LBC's

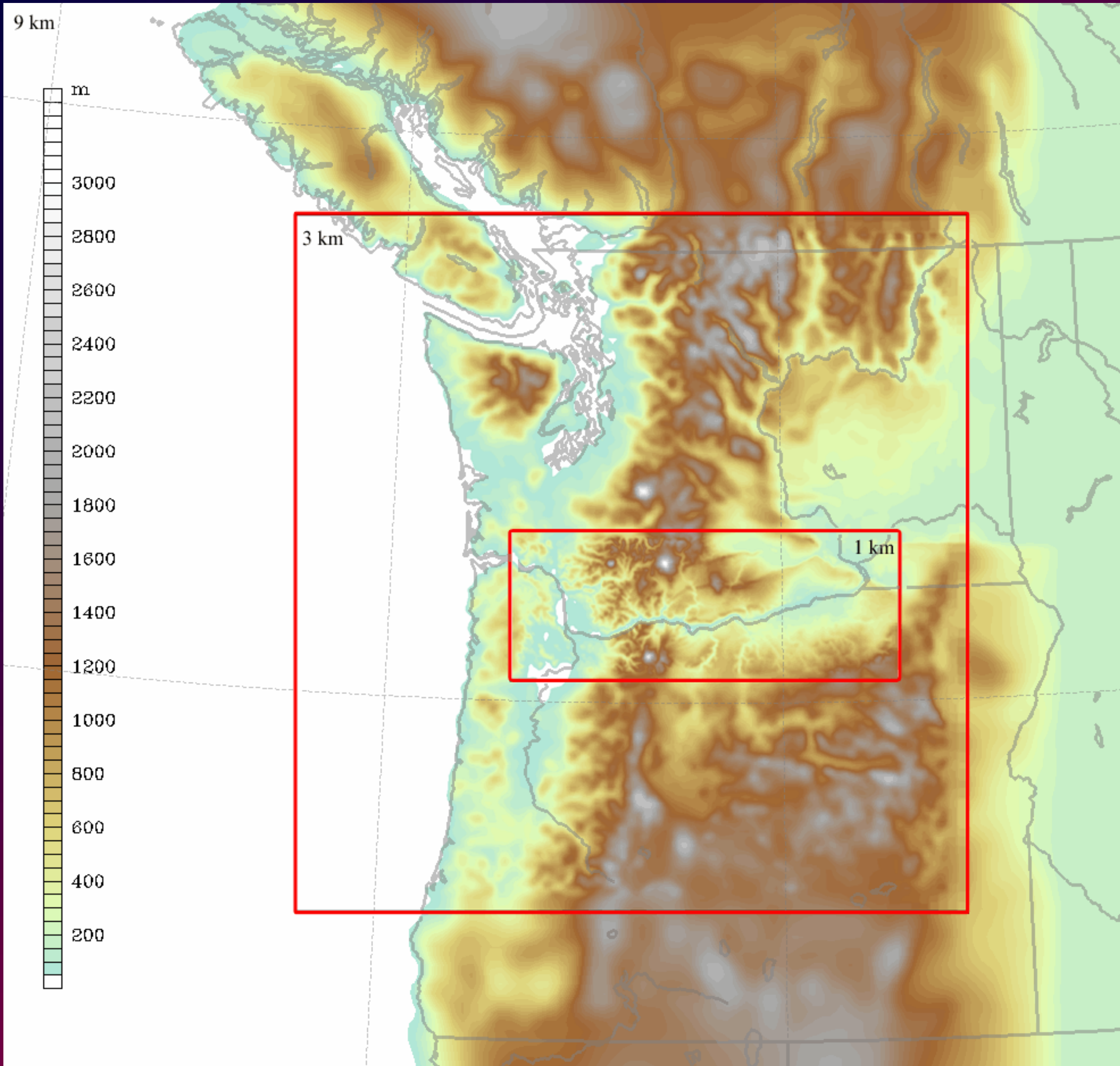
Model Setup For Idealized Sims

- Three nests
- No radiation
- Dry



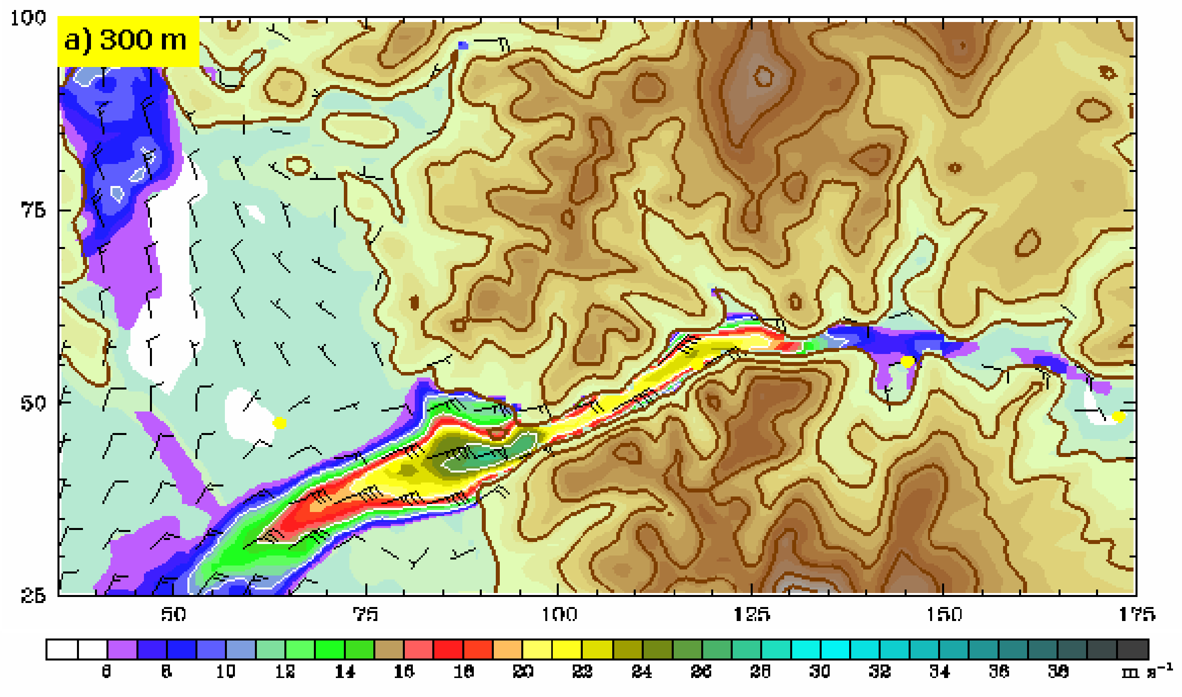
Model Setup For Idealized Sims

- Ideal Terrain
  - Flat eastern edge
  - Basin is now connected to lateral boundaries at low levels



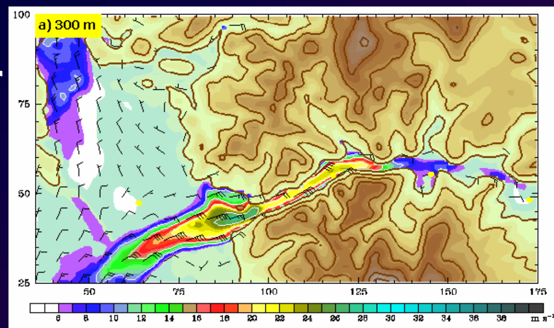
Results and Mechanisms - Venturi

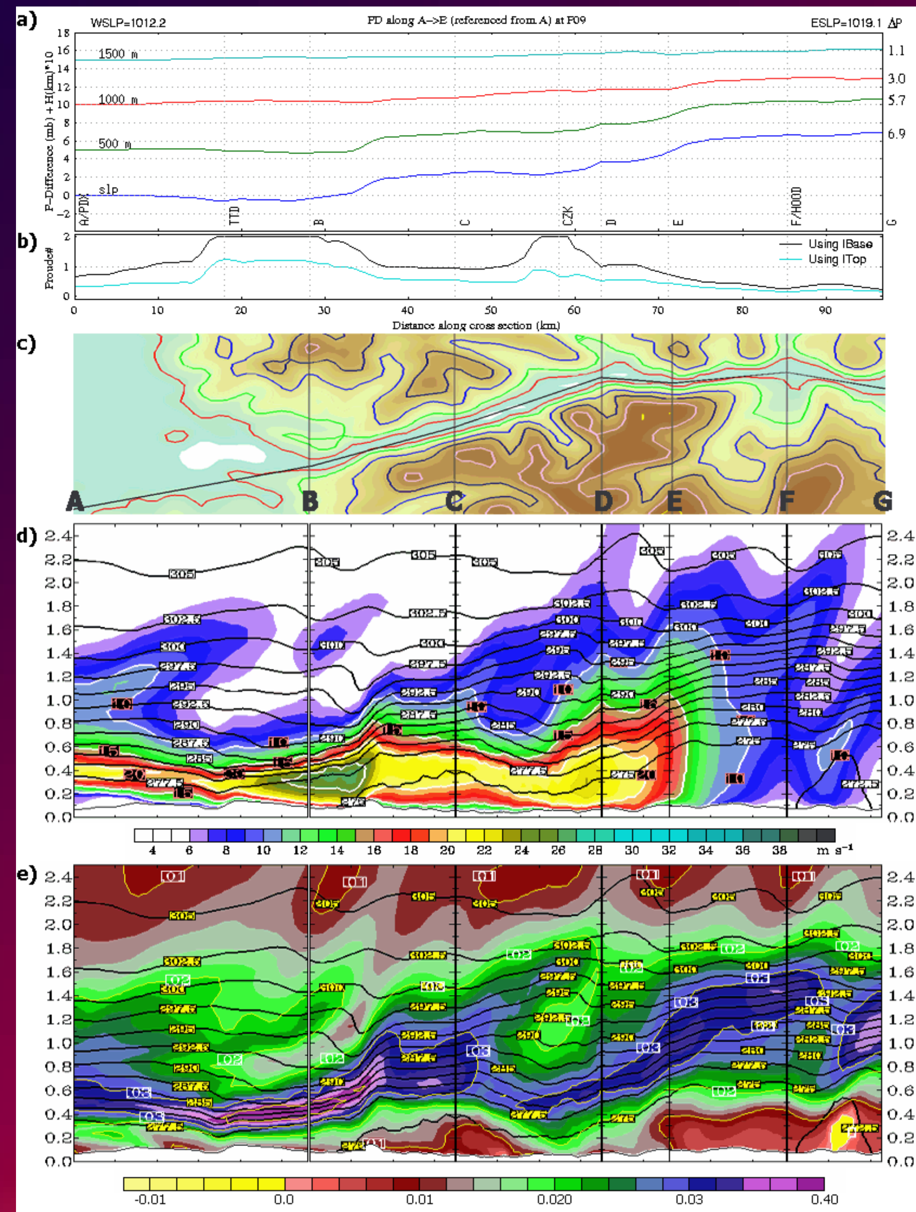
- Acceleration towards the crest is due to convergence into the narrow part of the Gorge 👍
- Acceleration as gap widens and at exit 👎
- The Venturi effect is NOT responsible for acceleration west of the Cascade crest. Similarly for other mesoscale gaps
- The Venturi Effect is still used in some introductory texts to explain gap flow!



Results and Mechanisms - Hydraulics

- First zone of strong acceleration occurs as flow passes through narrowest point in the gap and into an area of channel widening suggests transition to supercritical flow

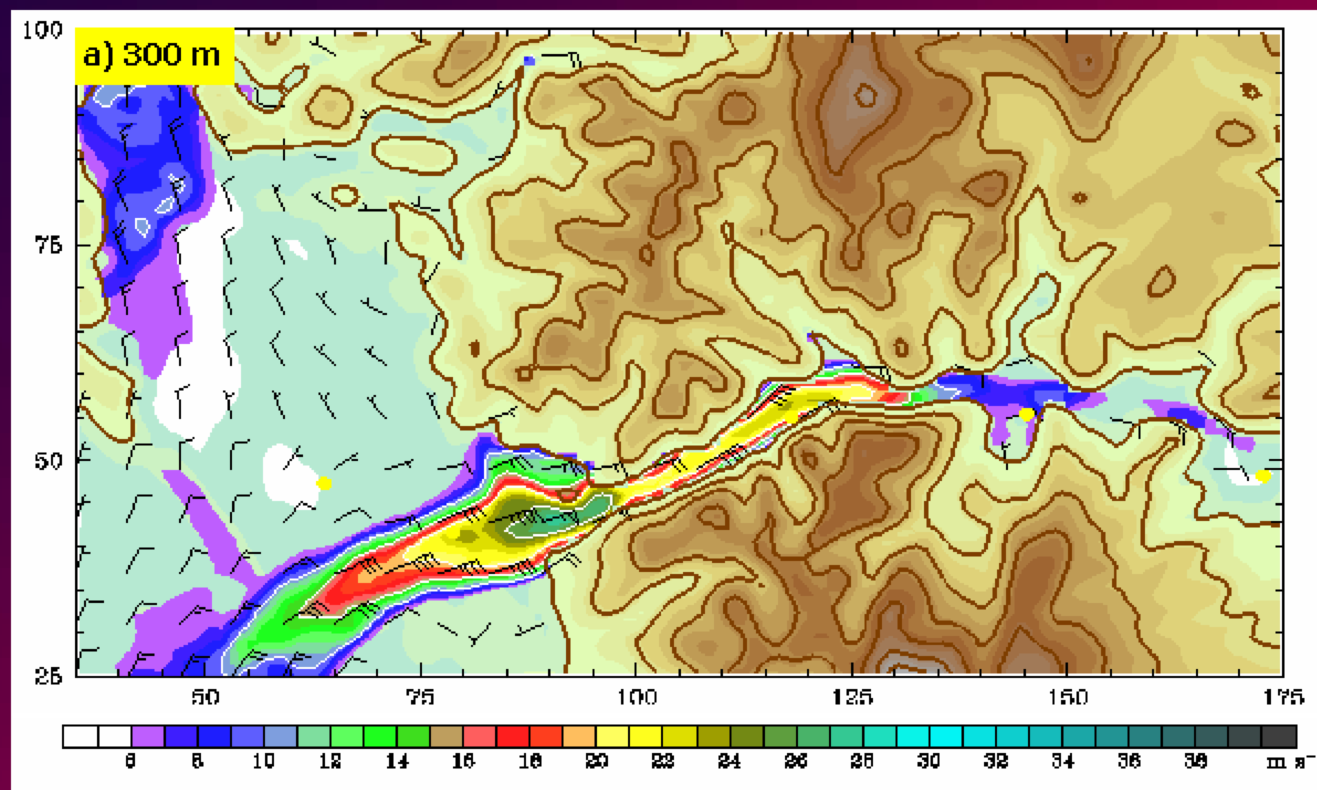




- Strong acceleration correlated with channel widening (infinite widening at the exit)
- Depth of gap flow layer appears to respond in a manner consistent with hydraulic theory

Hydraulics: Some Inconsistencies

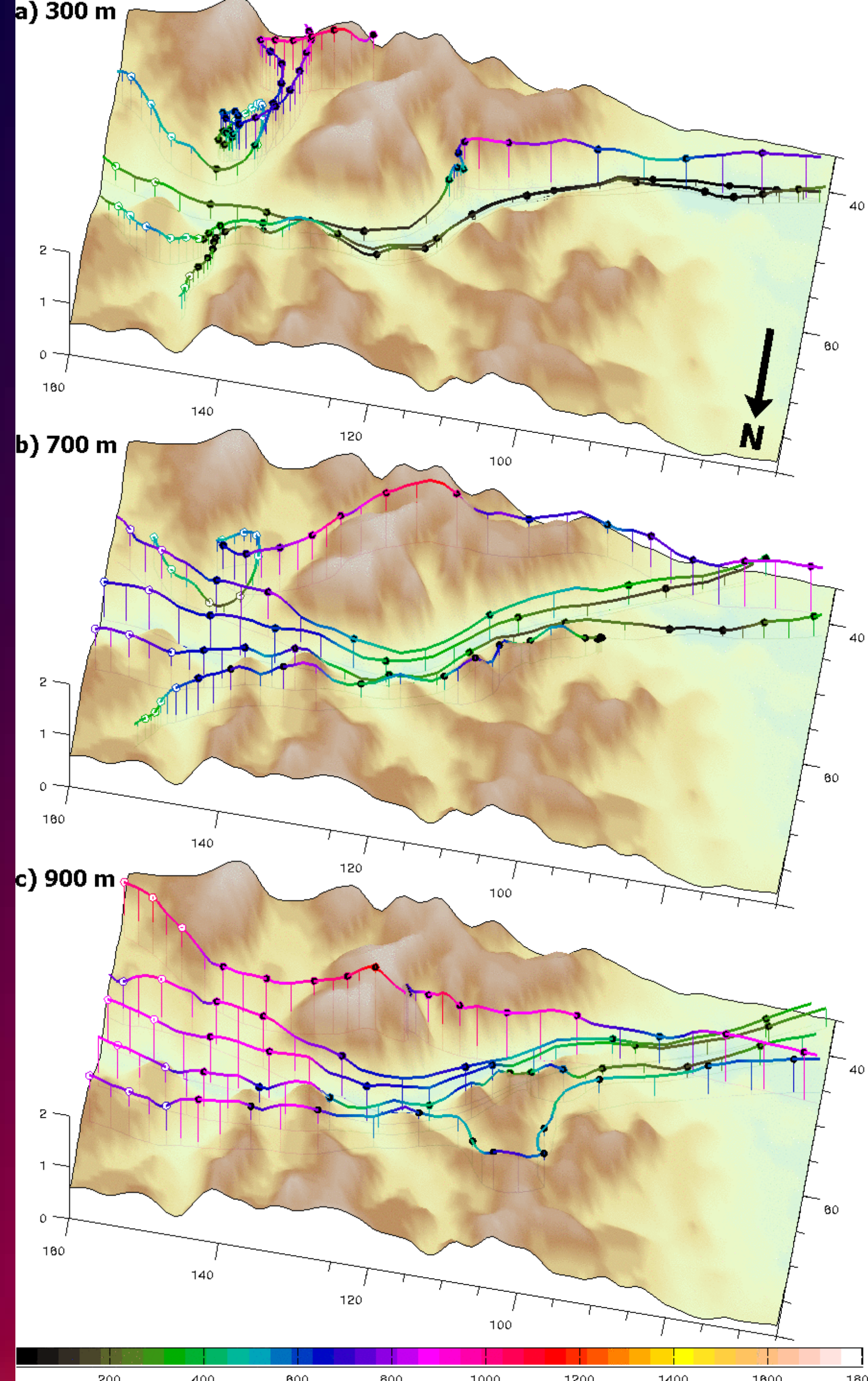
- Some acceleration zones are difficult to clearly map to lateral geometry changes
- Significant mixing occurs between the interface and the gap flow air
- The gap flow is very asymmetrical
  - Shown vividly next slide



Results and Mechanisms: Downslope

- Trajectories
  - Acceleration west of the crest is associated with descending parcels
- The preceding results indicate that Gorge gap flow is driven to a large degree by pressure gradients created by the interaction of nearby terrain with the mean flow
- This idea has recently been suggested for other level and elevated gaps and for gap exit regions
  - Exit of the Strait of Juan de Fuca
  - Brenner Pass
  - Hinlopenstretet

Take a virtual trip down the Gorge



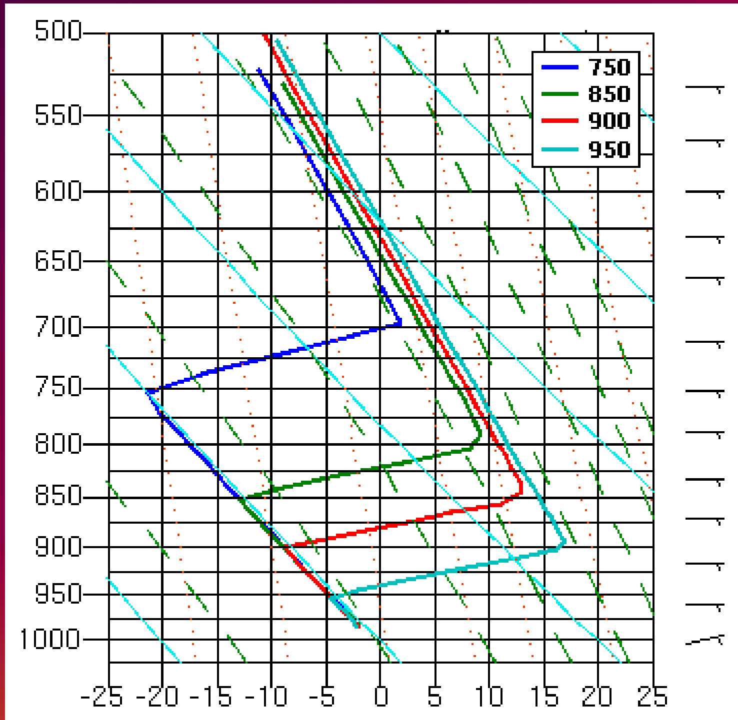
Width Changes or Downslope?

- What mechanism dominates west of the crest?
- Examine:
  - Behavior of low and high Froude number flow
  - How the Gorge gap flow responds to environmental factors that affect to gravity waves?

High versus Low Froude Number Flow

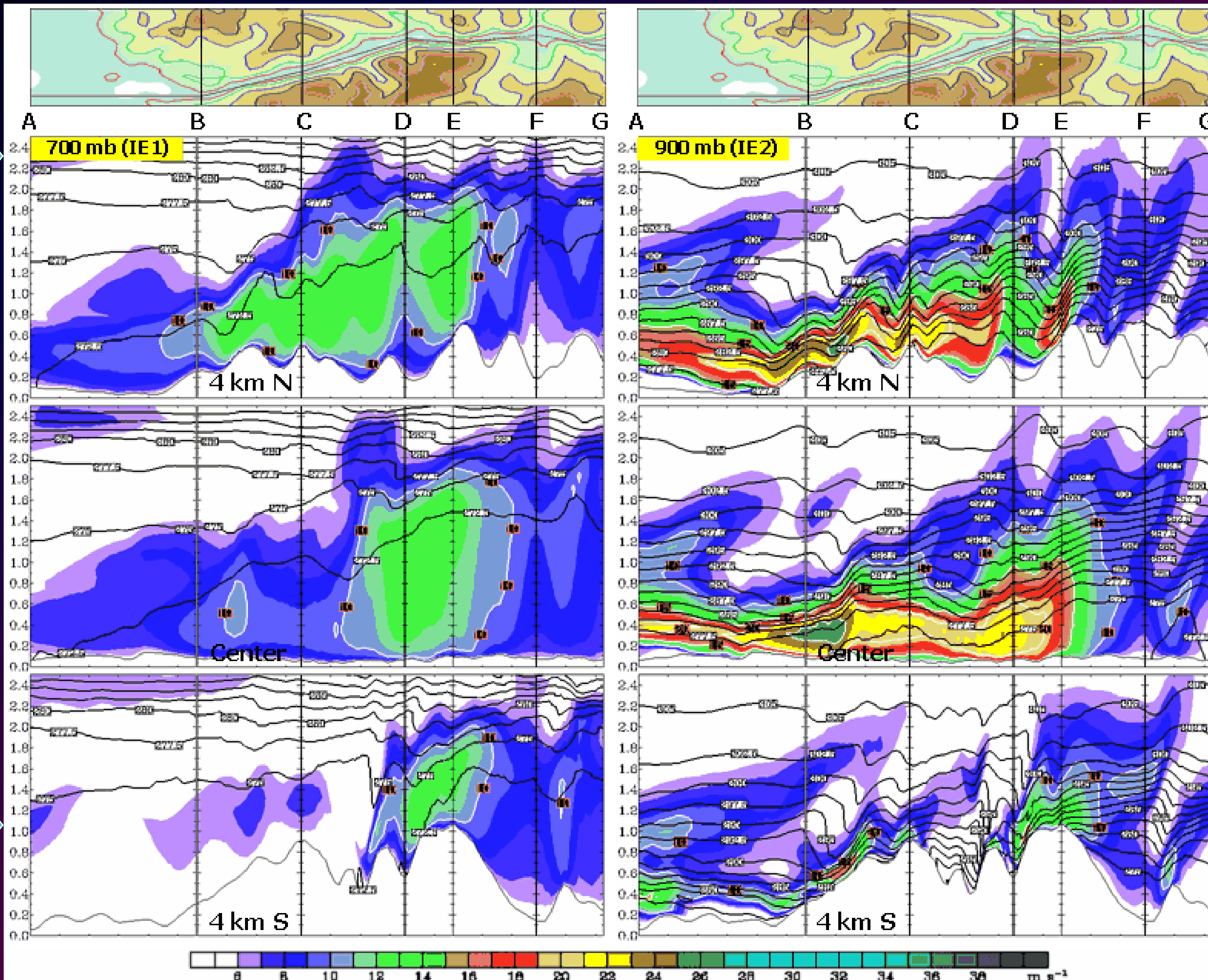
- Investigate effect of inversion depth on flow regime
  - Initial conditions defined to satisfy shallow water model as closely as possible
    - Well mixed lower layer, sharp inversion
  - Froude number decreases as depth is increased
    - Parameters other than D are initially constant
    - Expect a regime shift if initial depth is great enough that the flow will no longer become critical at the crest

$$F = \frac{u}{\sqrt{g \frac{\Delta\theta}{\theta} D}}$$



Qualitatively the four cases are actually fundamentally similar

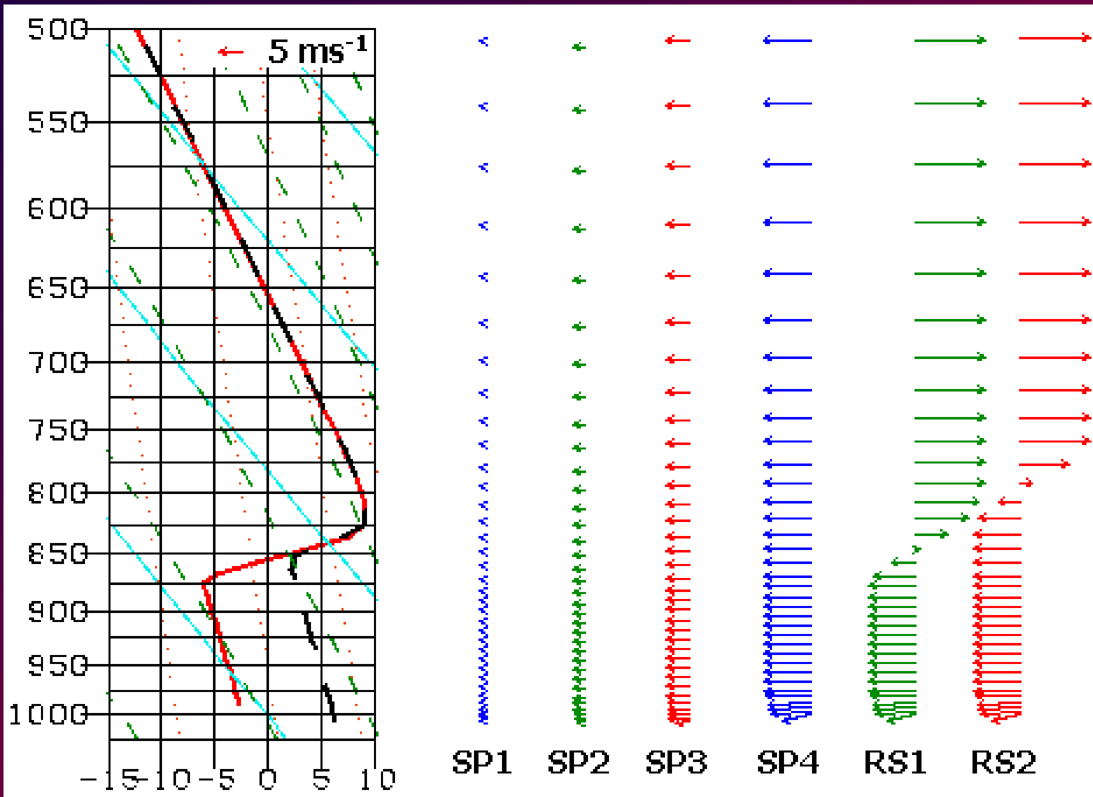
750 mb Inversion Base



900 mb Inversion Base

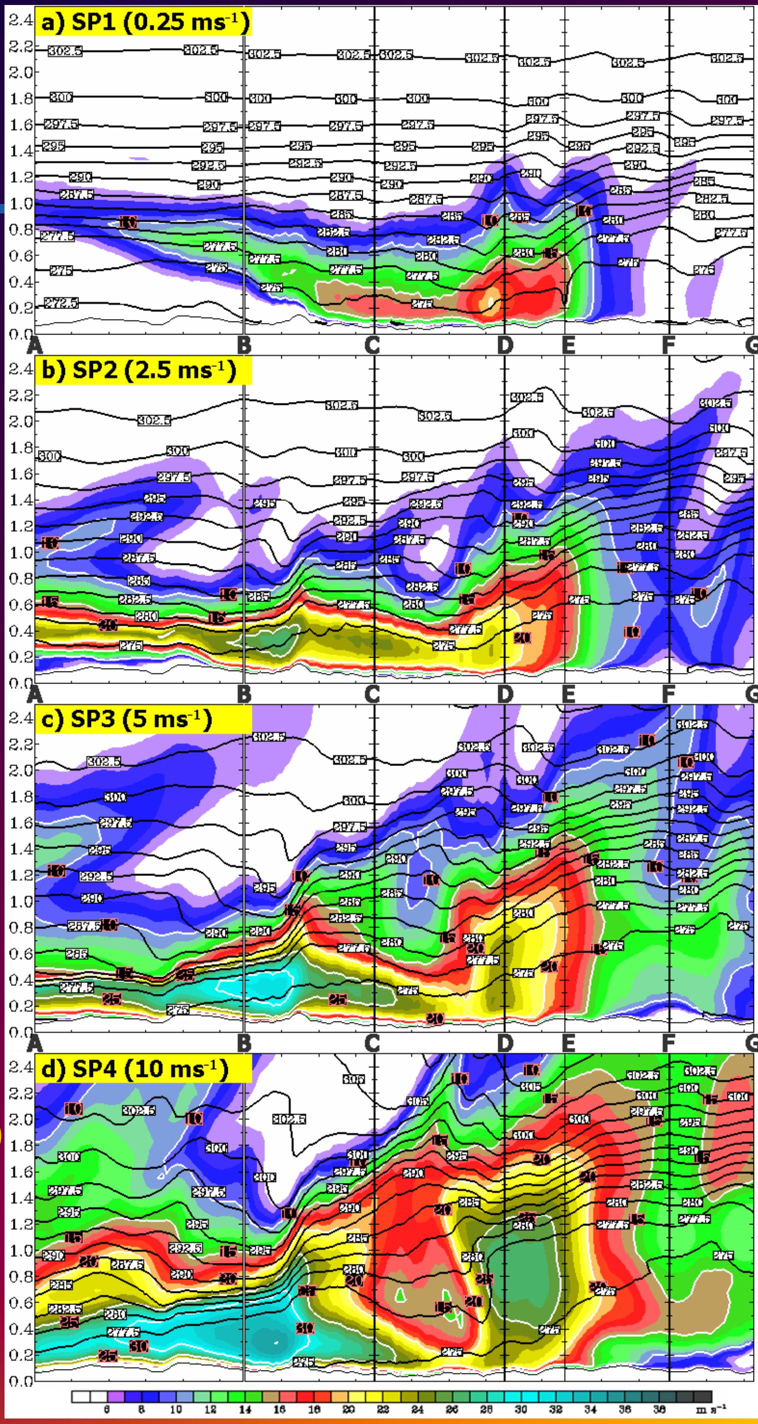
Environmental Wind and Gorge Gap Flow

- Many simulations performed to examine sensitivity to shear
  - Just effect of environmental flow speed is shown here
- Mixed layer, capped by strong inversion



Upstream Flow

- Evidence of wave effects:
  - Stronger descent as environmental flow speed increases
  - Larger waves especially at exit
  - No wave activity at exit for case with very weak initial flow. Flow lifts from surface
  - Very strong initial flow yields turbulent overturning to low levels near Cascade Locks reducing speed on the south side of the gap in that section



Summary and Conclusions

- Gap flow characteristics
  - Complex and highly 3-dimension in nature
  - Air has multiple sources at different elevations
  - Well defined acceleration zones that are correlated with terrain features
- Acceleration due to the Venturi effect is significant only in the convergent region upstream of the Cascade crest where it is an important mechanism for accelerating the flow to rates sufficient to interact with the terrain downstream

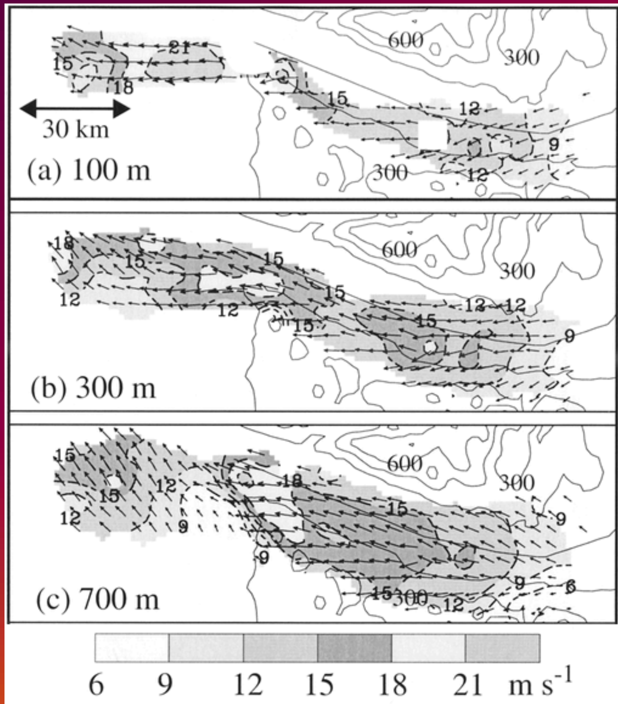
Summary and Conclusions (2)

- The strongest acceleration appears to be driven by pressure perturbations resulting from downslope winds and strong mixing as the flow interacts with the gap sidewalls
  - Strongest acceleration is close to the sidewalls
- Original hypothesis of acceleration due to gap width changes as prescribed by shallow water hydraulic theory is probably a secondary factor
- NOTE HOWEVER, that hydraulic dynamics (transitions to supercritical flow) are still relevant in understanding the downslope effects

Questions

A Brief History of Gap Flow Research

- Venturi Effect
  - A simple mass continuity theory
    - Flow speeds up at a constriction to conserve mass — Sometimes
    - Strongest winds/lowest pressure at narrowest point — NO!
    - Assumes no net change in height of the fluid — NO!
  - A popular early explanation for gap flow
    - Proposed by Reed (1931) as mechanism for gap flow in the Strait of Juan de Fuca
    - Implicit in many early descriptions of Gorge gap flow. E.g. "The Columbia Gorge Wind Funnel" (Graham, 1953)



A Brief History of Gap Flow Research

- Gap Flow Force Balances:
  - 1-D horizontal momentum Equation:

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left(\frac{u^2}{2}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} - fv - ku^2$$

  - Assuming steady state and neglecting Coriolis and friction gives Bernoulli’s equation:

$$\frac{\partial}{\partial x}\left(\frac{u^2}{2}\right) = -\frac{1}{\rho}\frac{\partial p}{\partial x} \xrightarrow{\text{integrate}} u_1^2 = u_0^2 - \frac{2\Delta P}{\rho}$$

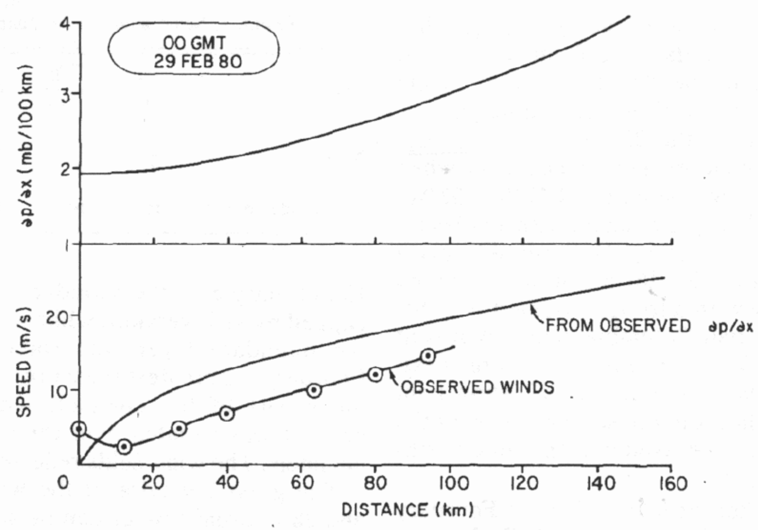


FIG. 20. Observed pressure gradient and winds for the Strait of Georgia. Also shown are computed winds from (2) using the observed pressure gradient.

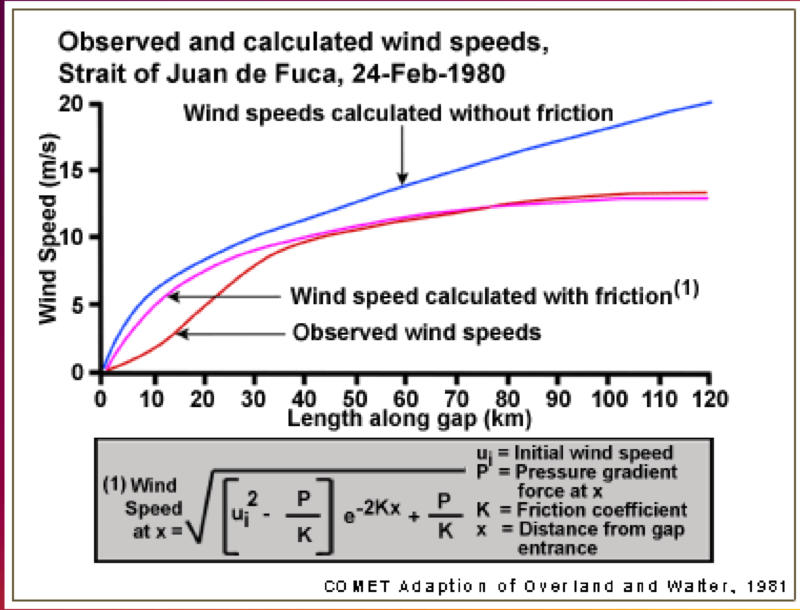
- Oversimplification that provides an upper limit to maximum speed at the end of the gap
  - E.g. Walter and Overland (1981), Reed (1981)
- Gap winds are a boundary layer phenomena
  - Must account for drag (both surface drag and drag at upper interface)

A Brief History of Gap Flow Research

- Reintroducing friction yields *antitriptic* balance

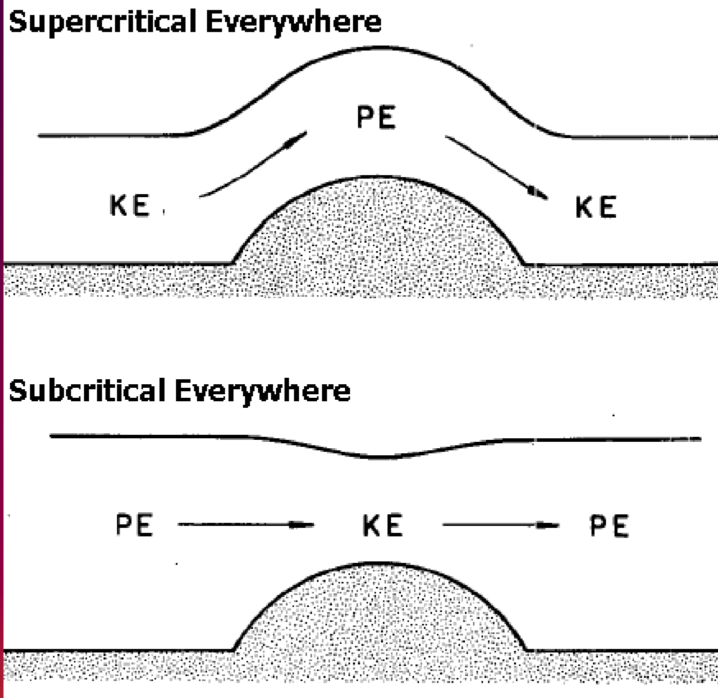
$$\frac{\partial u}{\partial t}+\frac{\partial}{\partial x}\left(\frac{u^2}{2}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}-ku^2 \xrightarrow{\text{integrate}} u_1^2=\left[u_0^2-\frac{\Delta p}{k\rho}\right]e^{-2kx}+\frac{\Delta p}{k\rho} \quad \text{where } k=\frac{2.8C_D}{H}$$

  - Three way balance between acceleration, PGF and drag
- Produces a much closer correlation to observed winds **at the end of long, relatively wide gaps**
  - E.g. Lackmann and Overland (1989), Mass et al (1995), Colle and Mass (1986), Bond and Stabeno (1998)
- Assumes no along gap elevation change (this can be accommodated though)
- Does not fully explain the complex structures and transitions seen in many gap flows, including Gorge flow.



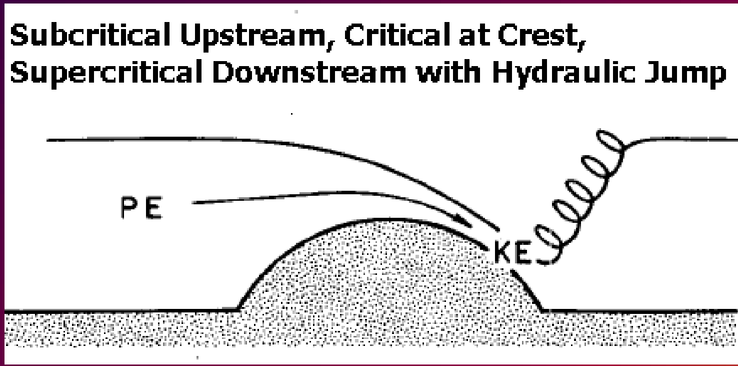
A Brief History of Gap Flow Research

- Hydraulic Theory
  - In a <u>well mixed</u> gap flow bounded above by a <u>sharp</u> density discontinuity (inversion) the Froude Number $F = \frac{u}{\sqrt{g \frac{\Delta\theta}{\theta} D}}$ determines the response of the flow to changes in channel width and/or bottom topography
  - F>1 (supercritical): Flow slows and deepens approaching constrictions, accelerates and thins as gap widens
  - F<1 (subcritical): Flow accelerates and thins approaching constriction/ crest, slows and deepens in region of widening/height decrease (Venturi flow)



A Brief History of Gap Flow Research

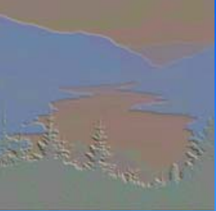
- Thinning of subcritical flow approaching constriction/crest can lead to flow becoming critical (F=1) at narrowest/highest point with a transition to supercritical flow downstream gap widens



- Flow will then continue to accelerate and thin until it is forced to adjust in a hydraulic jump
- When hydraulic theory is applied to level gaps, channel width changes act as hydraulic controls forcing state transitions
  - E.g. Application to Howe Sound, BC by Jackson and Steyn (1994)
- When applied to elevated gaps where gap sills and lateral geometry both define control points

A Brief History of Gap Flow Research

- The Downslope/Wave Mechanism
  - Several authors have recently suggested that mountain waves may play an important role in enhancing gap flow (e.g. Flamant et al 2002, Gabersek and Durran, 2004)
  - Mountain waves excited by terrain within the gap and at the exit may cause:
    - Strong downward momentum transport
    - Large pressure gradients
    - Substantial mixing
- Currently a vigorous debate about the relative importance of wave and hydraulic mechanisms
- If important, then gap flow should be respond to environmental factors affecting gravity waves



Questions

- Low Froude number flow was found to be fundamentally similar to flow with high Froude number
- Does Gorge gap flow should be respond to environmental factors affecting to gravity waves?