Hydraulic jumps and cloud formation on Mars

Mesoscale Dynamics Related to an Elongated Cloud over Tharsis Montes on Mars

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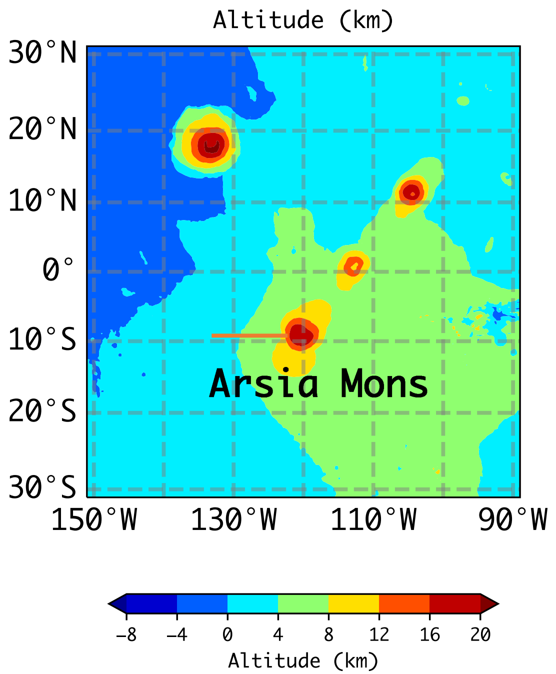


(←) Tharsis Montes

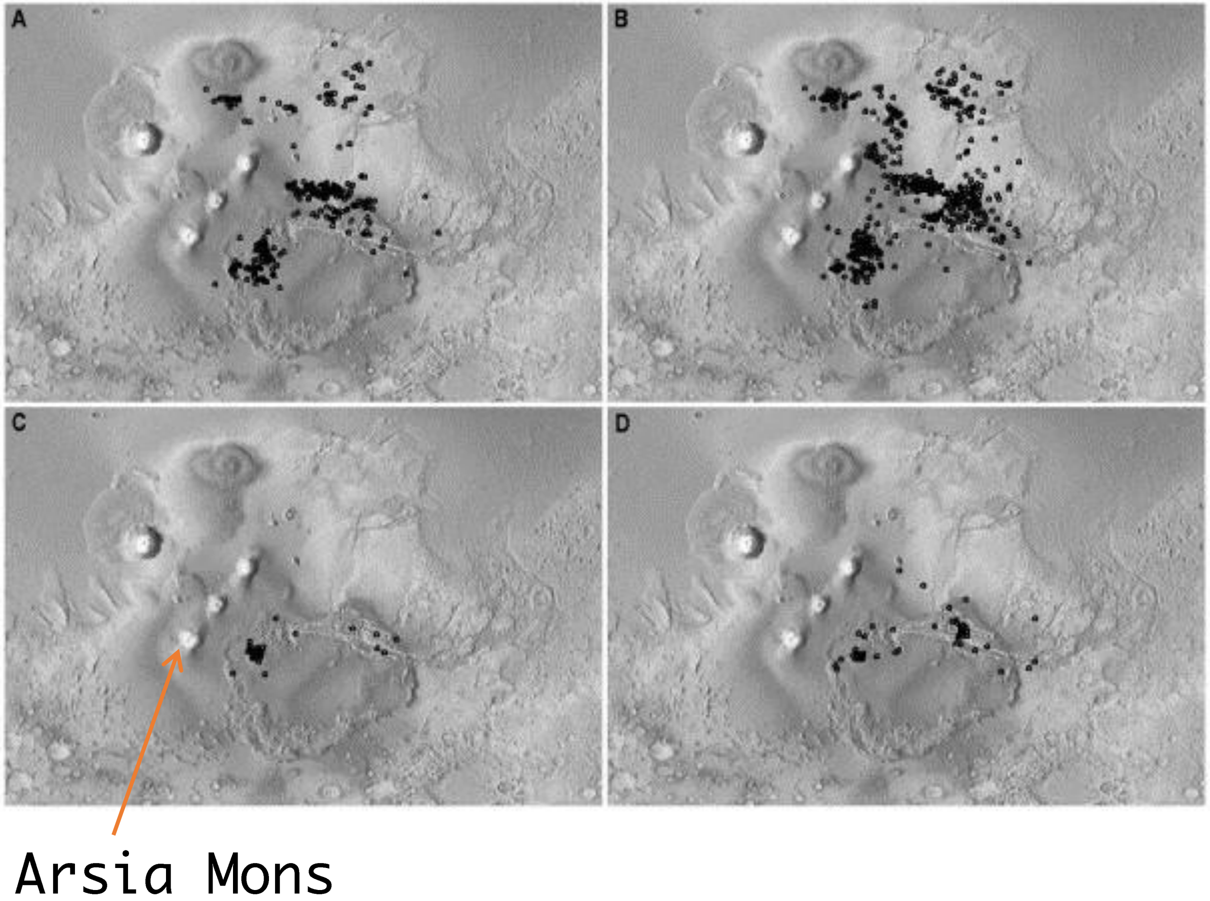
- Three large shield volcanoes in the Tharsis region.
- Specifications: Enormous by terrestrial standards

Arsia Mons Elongated Cloud

1. AMEC, a seasonally-recurring mesoscale event, shows regular annual patterns, indicative of potential regulation by a broader climatic system.

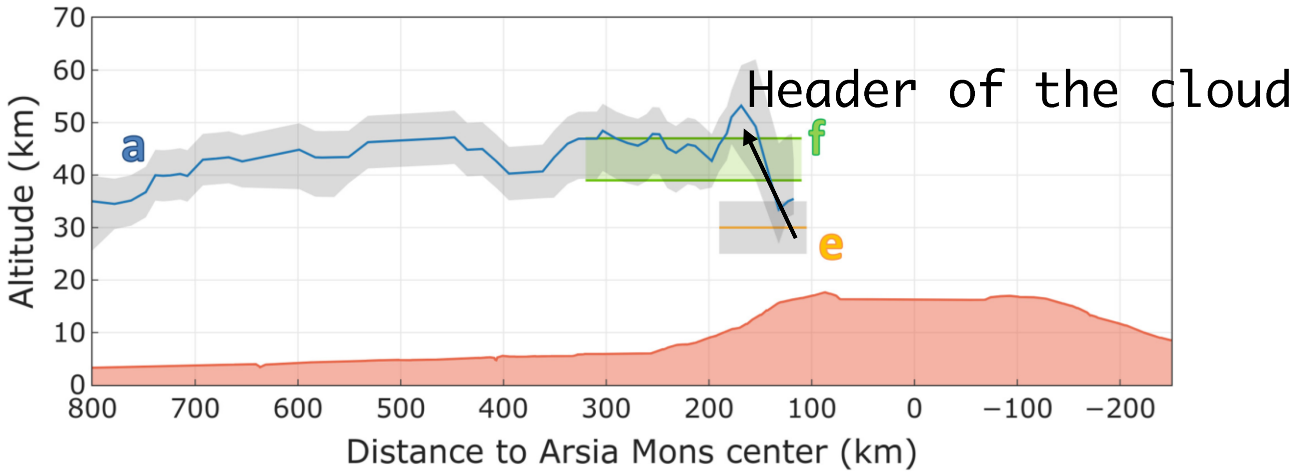
2. This cloud stretches up to 1,800 km west from Arsia Mons daily, around the Southern solstice at 220°–320° Ls.

Previous Study- Cloud center locations in Valles Marineris canyon and surface features. (Benson et al., 2003.)

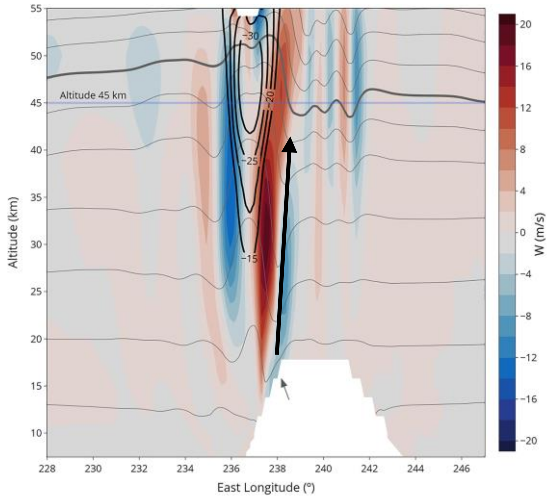


(A) L_s=0°-90°
(B) L_s=90°-180°
(C) L_s=180°-270°
(D) L_s=270°-360°

The clustering trend of cloud centers near Arsia Mons suggests a potential correlation during the AMEC season.



HRSC (High-Resolution Stereo Camera) capture of AMEC



Numerical simulation of vertical wind velocity

Previous Study

- Hernández-Bernal, et al. (2021 & 2022)

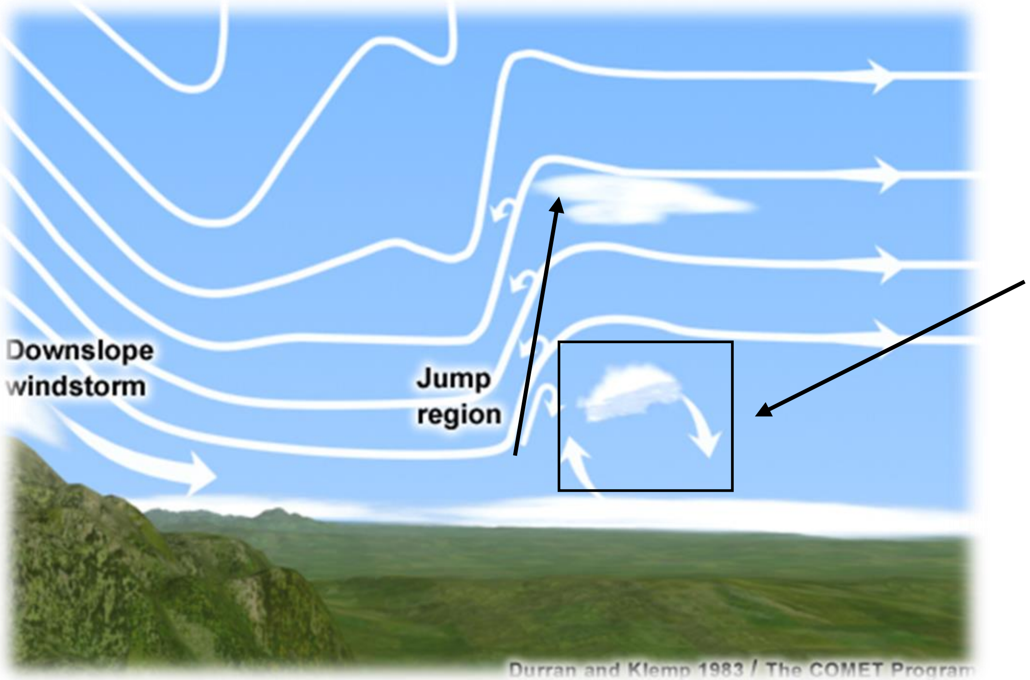
This study utilizes numerical simulations to explore Arsia Mons' atmospheric impact during AMEC, linking it to a hydraulic jump/(stationary wave).

This study connects stationary wave updraft with AMEC's formation height and notes the coincidence with Arsia Mons' peak zonal winds.

The direct link between these winds and AMEC's formation remains unclear, with potential alternative factors acknowledged.

Hydraulic Jump

- A hydraulic jump is a sudden shift from fast to slow flow in atmosphere and channels due to fluid dynamics.
  - Hydraulic jumps occur when fluid flows too fast for gravity waves to travel upstream, wherein the fluid becomes unstable and suddenly readjusts to a turbulent, slower flow.
  - Hydraulic jump occurs on the lee side of the mountain, strong winds will occur along the lee slope when the fluid undergoes a transition from subcritical flow upstream to supercritical flow over the mountain.



Secondary Circulation

Research Purpose

- To understand what factors do influence the hydraulic jump associated with AMEC
  - Shape of the mountain
  - Wind Velocity
  - Surrounding
  - …?

Methodology:

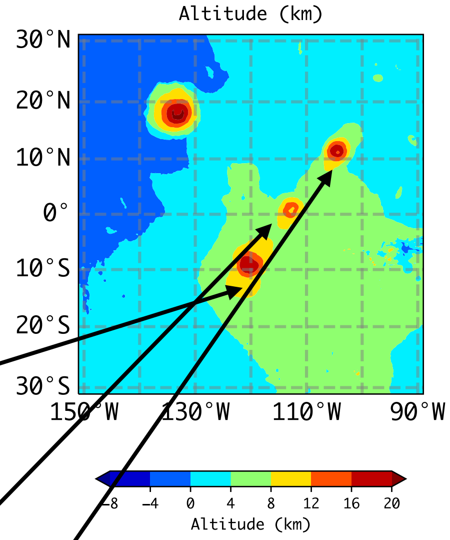
- Numerical simulation with idealized mountains
- Testing conclusions on numerical simulations with MOLA topography and GCM

CReSS-Mars / Original and My Work

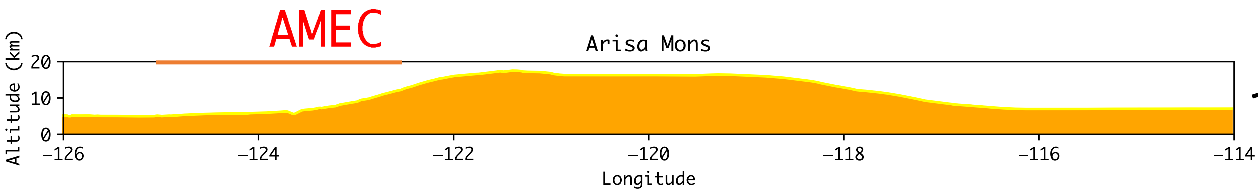
- **Model Specification**: 3-D regional
- **Dynamics**: Non-hydrostatic, compressible.
- **Coordinate System**: Terrain-following
- **Resolution**
  - (1000m, 1000m, 500m) for idealized simulation
  - (0.0625°, 0.0625°, 500m) for realistic simulation

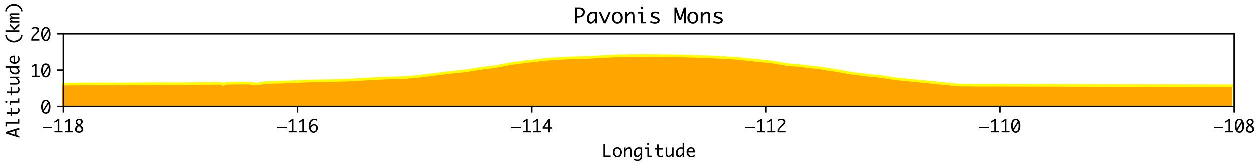
- **Fortran Standard**: Updated to Fortran 2008 and introduced of NVIDIA CUDA to refresh certain functional components.
- **Tensor Computing**: Some computational steps executed on 32 NVIDIA A100 GPUs.
- **New Boundary Condition**: New Methods for Handling Perturbation and Convection.

Shape of the Mountain

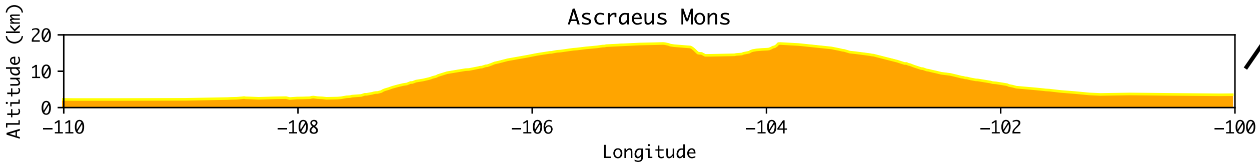


Flat top surface (mesa-shaped)





Non-flat top surface (bell-shaped)



- Arsia Mons is the only one has a flat top surface.
- The other two Tharsis Montes resemble bell-shaped mountains.
- Elongated cloud was only observed near Arsia Mons
- Comparison clarifies the role of flat tops in atmospheric dynamics.

Idealized Simulations

Idealized simulations highlight the key aspects of a problem.

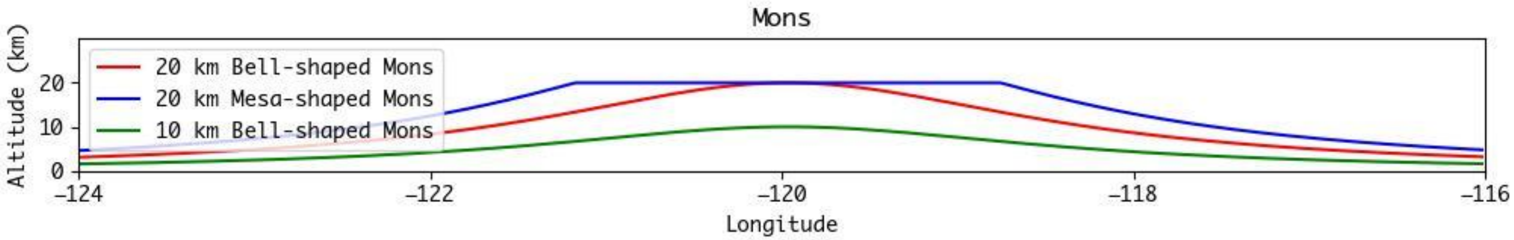
In our idealized experiments, we primarily focus on:

1. The initial horizontal wind speed.

    We consider several wind profiles.

    This study considers 60m/s and 10m/s scenarios, typical summer speeds in this region.

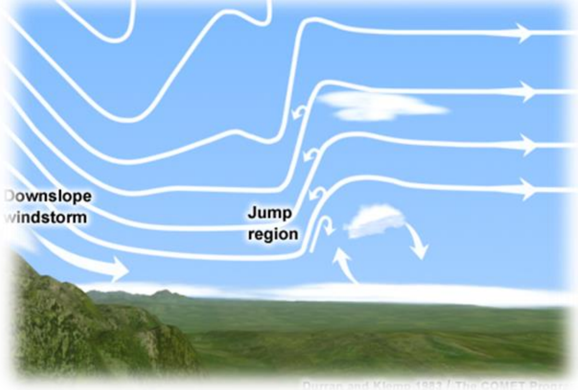
2. An idealized mountain.



	60m/s	10m/s
20km bell-shaped	√	√
20km mesa-shaped	√	√
10km bell-shaped	√	×

Strong updraft in Idealized Simulation (20 km Bell-shaped Mountain)

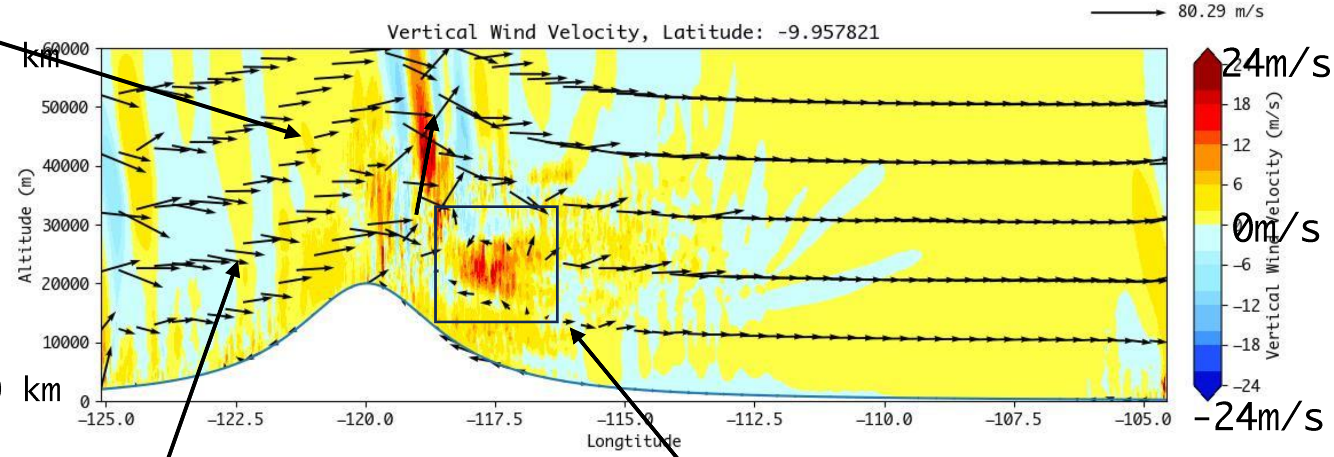
60 m/s



Horizontal cross section of vertical velocity (30 km above surface)

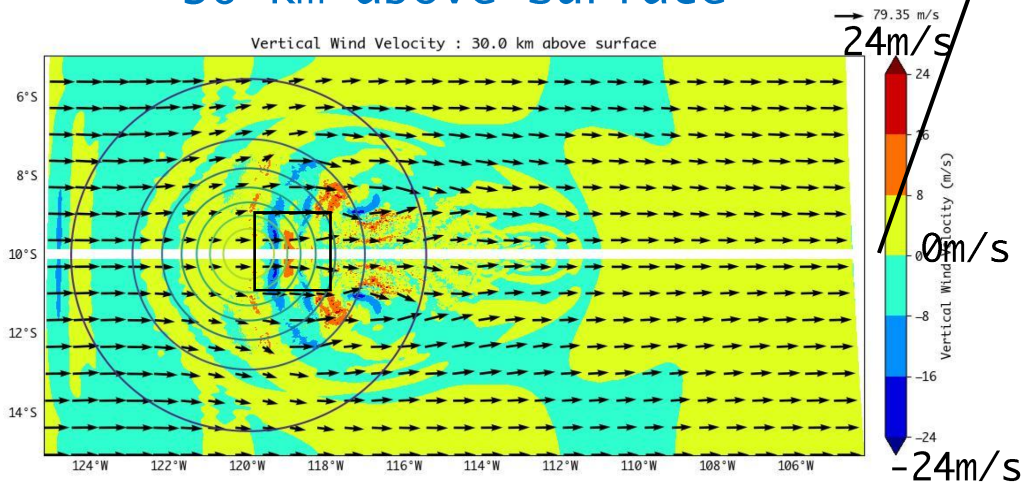
Hydraulic Jump

Vertical cross section of vertical wind velocity



Secondary Circulation

30 km above surface

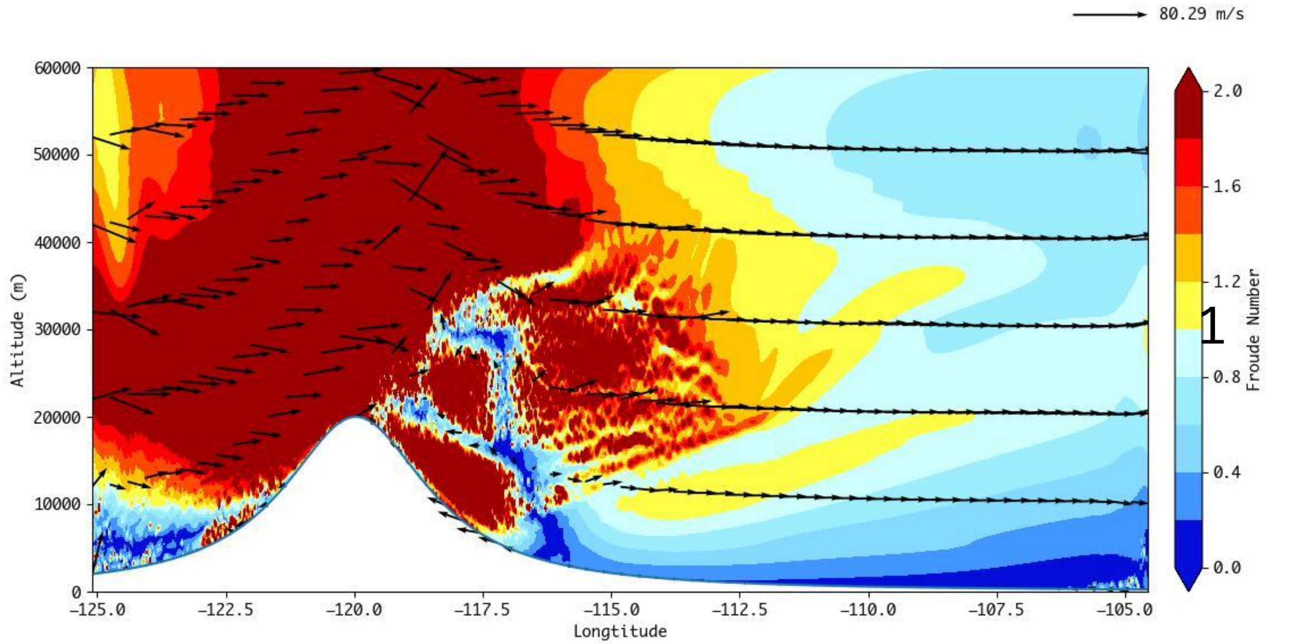


Strong updrafts start at leeward slopes with secondary circulation

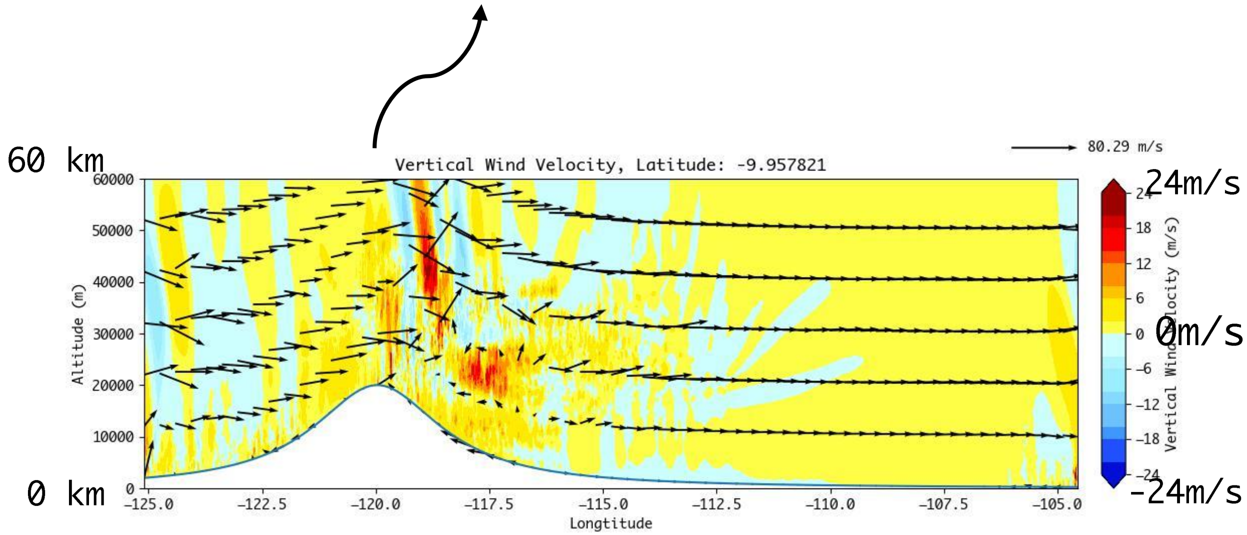
Froude Number

$$F = \frac{\sqrt{2KE}}{NH}$$

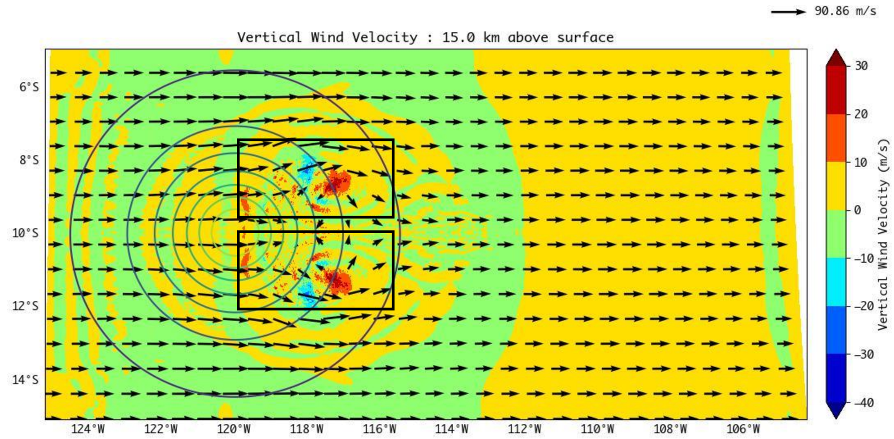
N: Buoyancy Frequency
H: Scale Height
KE: $\frac{u^2+v^2}{2}$



$F > 1$: supercritical flow
$F < 1$: subcritical flow

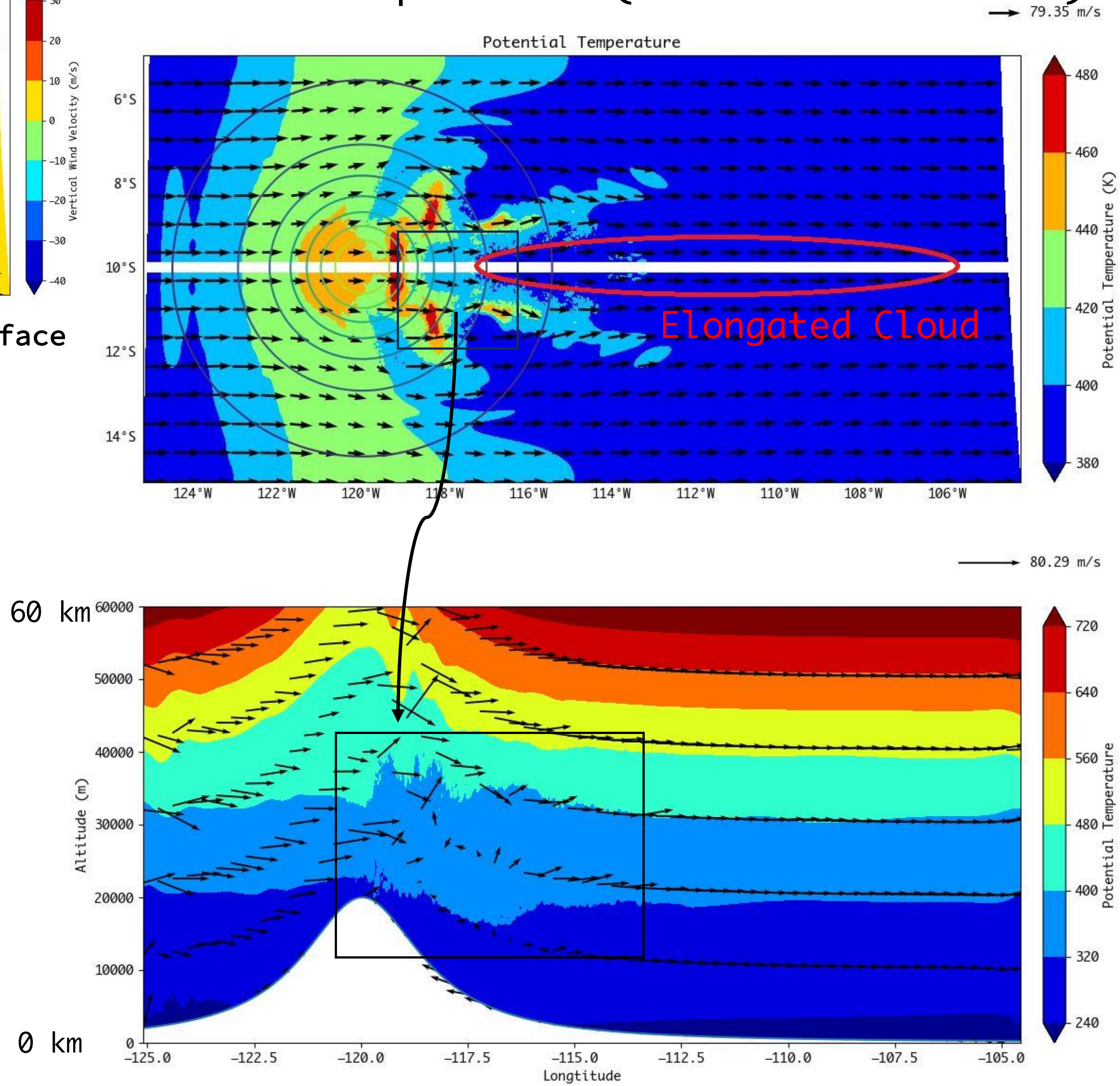


- Large Froude number areas outline the shape of the hydraulic jump.
- Also shows the secondary circulation excited by the hydraulic jump.



Vertical Wind Velocity at 15 km above surface

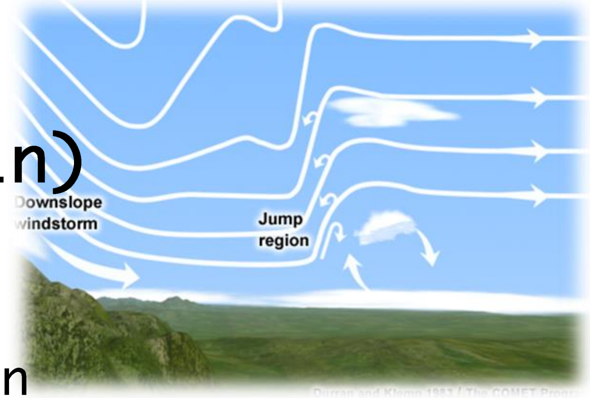
Potential Temperature (30km above surface)



1. Two tentacle-like patterns(branches) noted, reminds us of a previous study.

2. Clouds forming leeward face directional growth due to high-potential temperature branches.

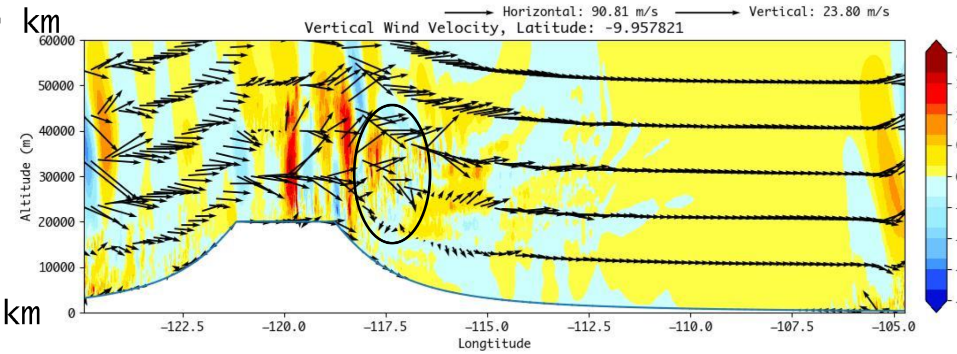
Sensitivity to the mountain shape
(20 km Mesa-shaped and Bell-shaped Mountain)



60 m/s

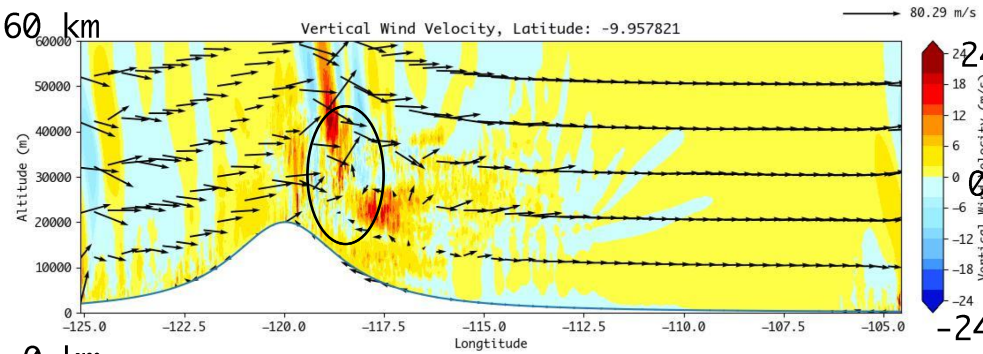
mesa-shaped mountain

60 km
0 km
24m/s
0m/s
-24m/s

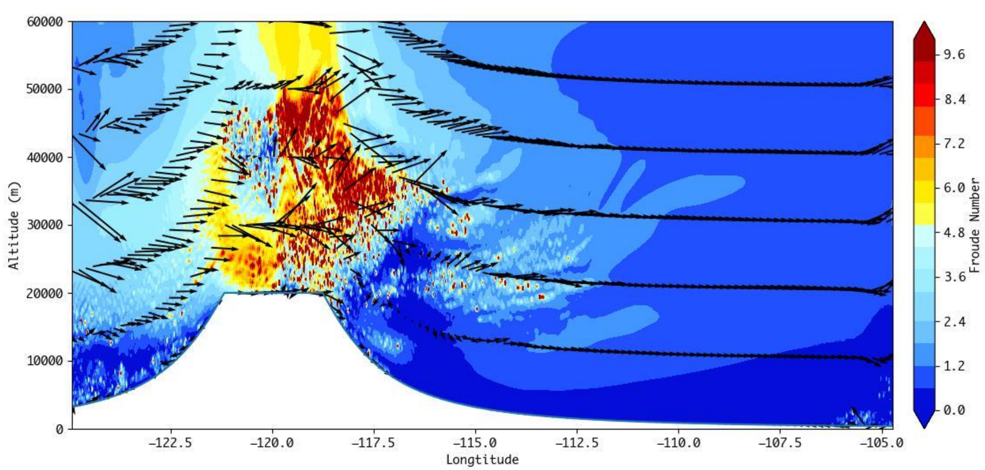


bell-shaped mountain

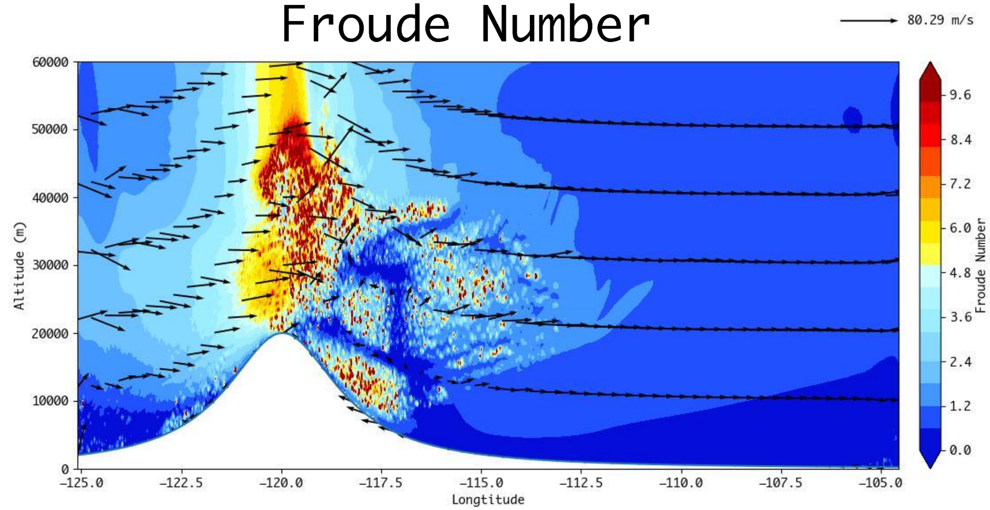
60 km
0 km
24m/s
0m/s
-24m/s



Froude Number



Froude Number

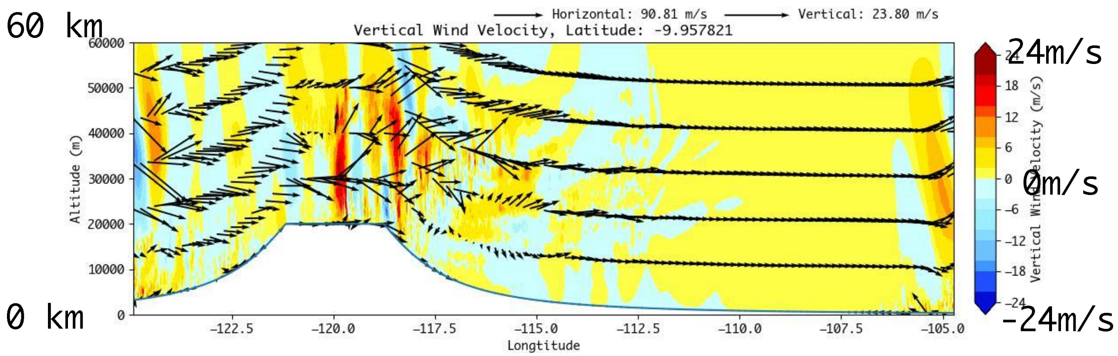


Much stronger vertical wind velocity in the mesa-shaped case.
Possible Reason: Different horizontal wind acceleration near the top

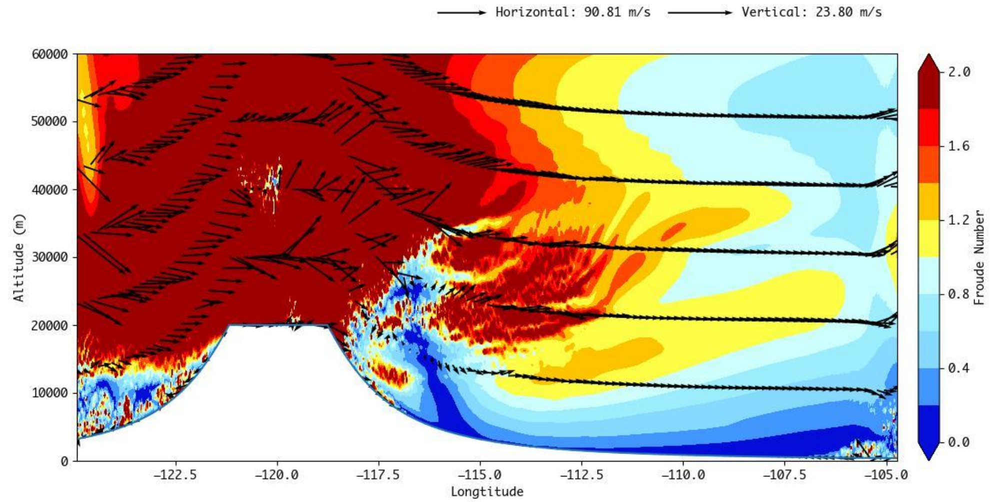
Sensitivity to
The background wind velocity

Background Wind Velocity: 60m/s

Cross-Section Vertical Wind Velocity

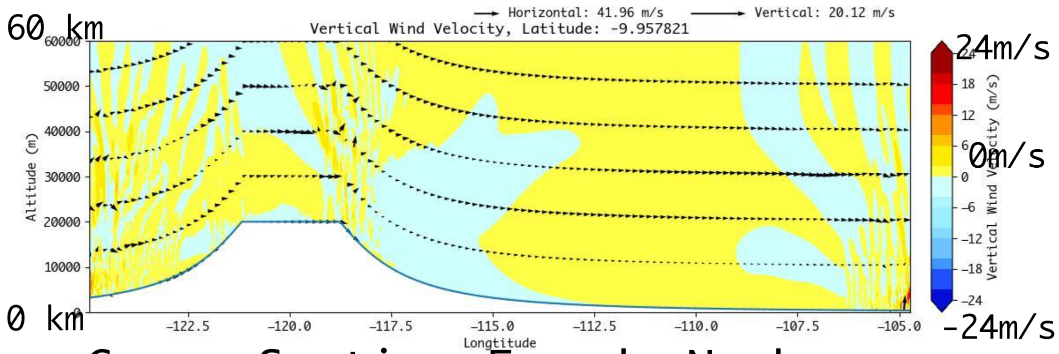


Cross-Section Froude Number

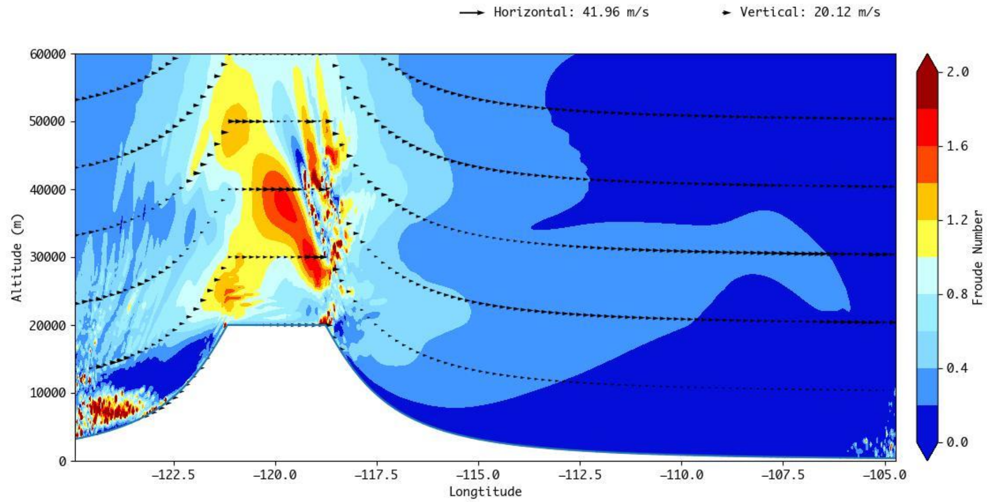


Background Wind Velocity: 10m/s

Cross-Section Vertical Wind Velocity



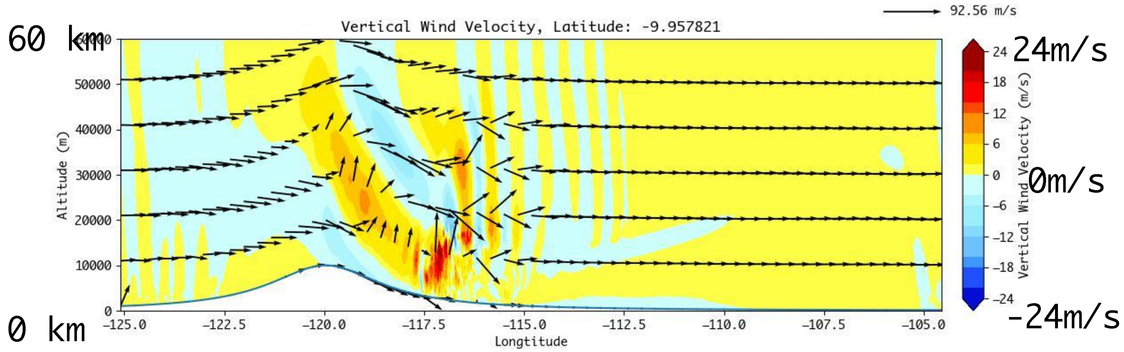
Cross-Section Froude Number

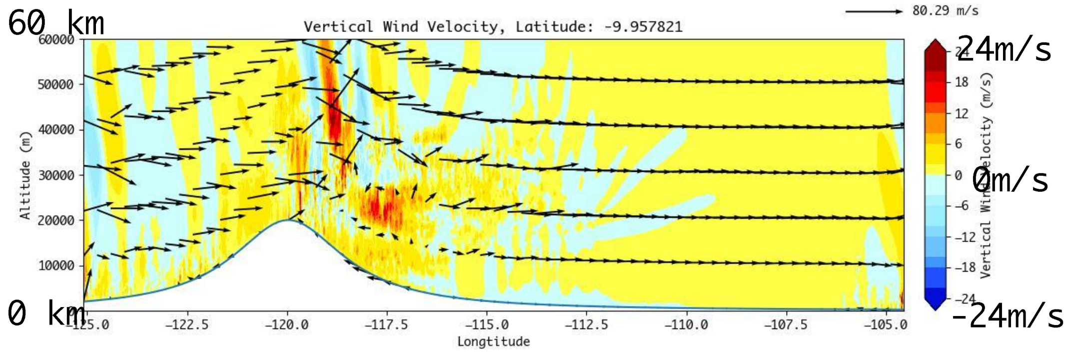


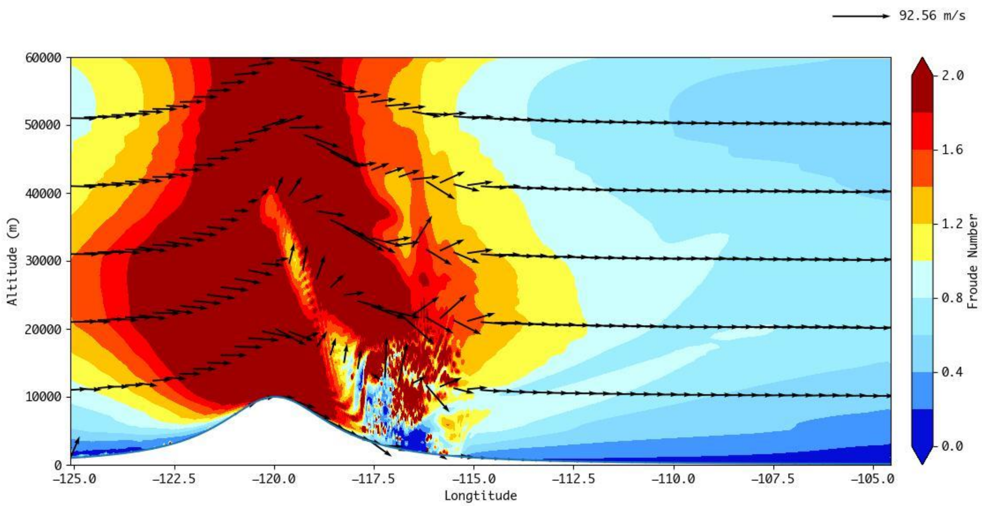
Higher wind speeds are associated with more pronounced hydraulic jumps.

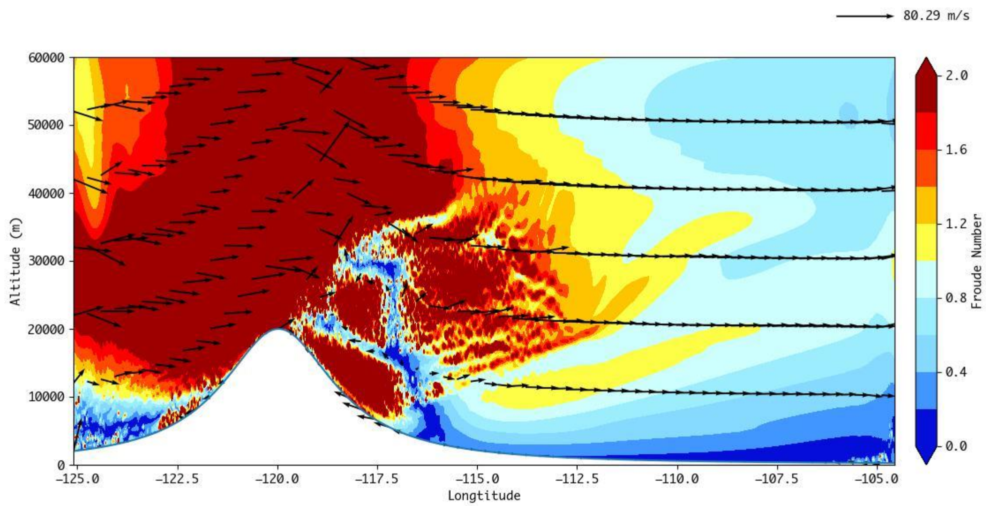
Sensitivity to Mountain Height

Higher mountain results in a significant hydraulic jump.









10 km top height

20 km top height

Conclusion of sensitivity test

	60m/s	10m/s
20km bell-shaped	Moderate	Negligible
20km mesa-shaped	Strong	Negligible
10km bell-shaped	Weak	×

Arsia Mons

- Mountain shape, background wind velocity and mountain height are found to influence the hydraulic jump

- The horizontal wind velocity near the top of the mountain controls the hydraulic jump

Realistic Simulation With Realistic Topography and Mars GCM for initial condition

1. Realistic topography applied
   Mars Orbiter Laser Altimeter (MOLA) Mars Topography

2. GCM for Initialization: DCPAM (Dennou-Club Planetary Atmospheric Model Project)

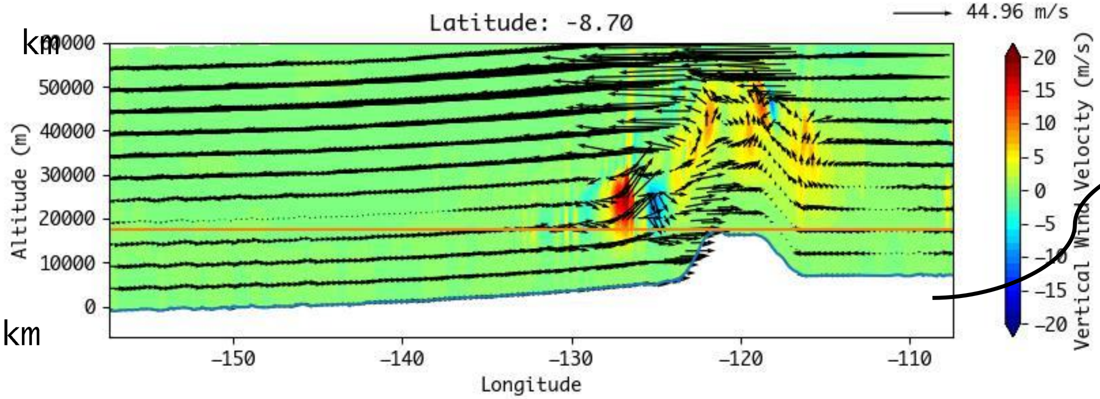
3. Exclusion of Cloud Physics

4. Isolated Arsia Mons and Arsia Mons in the context of Tharsis Montes

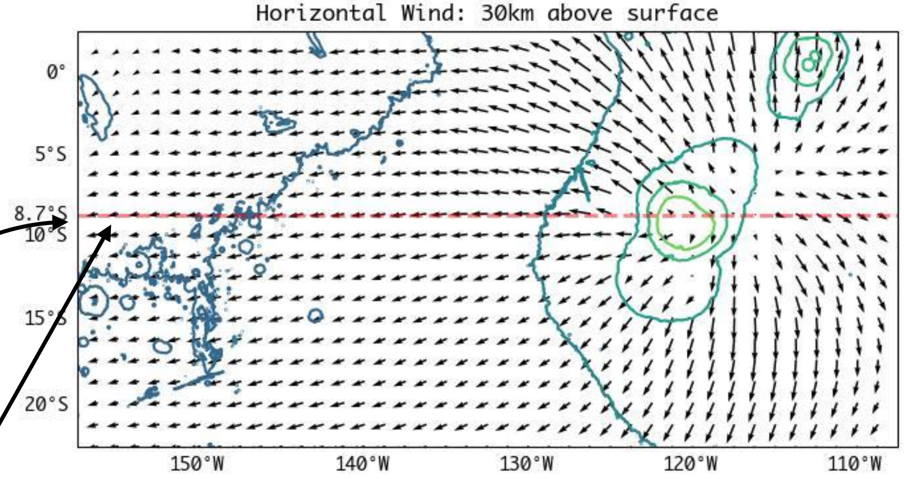
The Challenge of Realistic Simulation

Vertical resolution: 500m

60 km

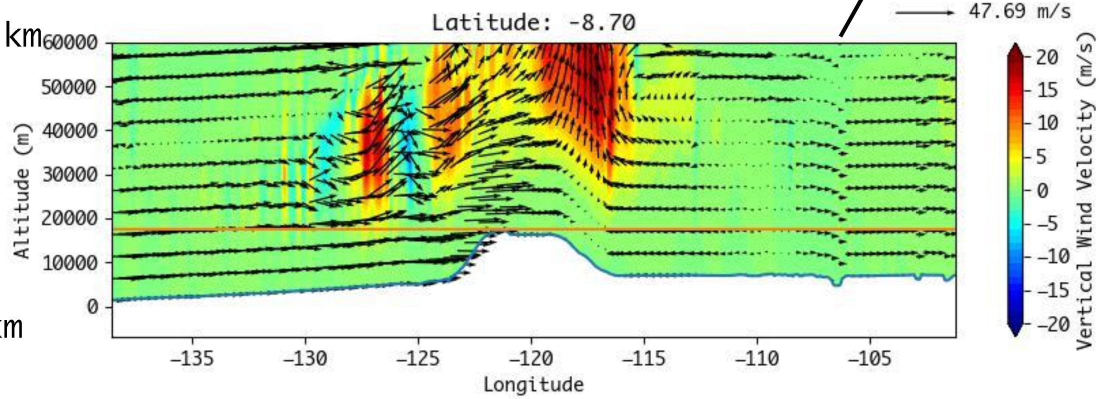


0 km



Vertical resolution: 250m

60 km



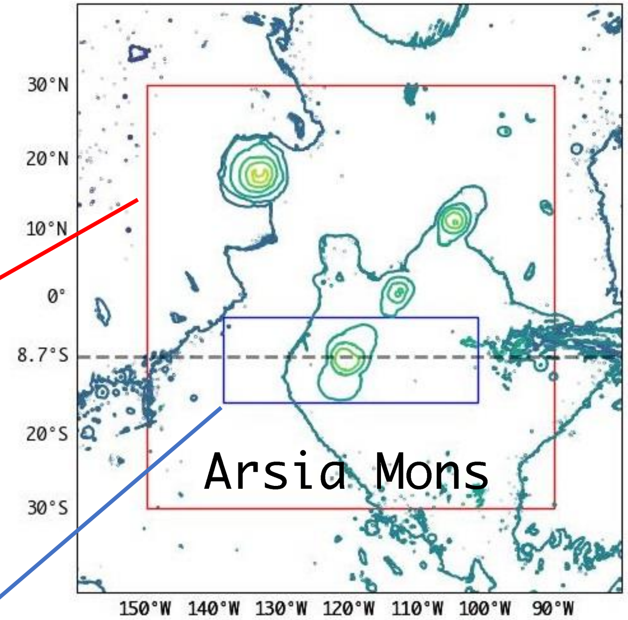
0 km

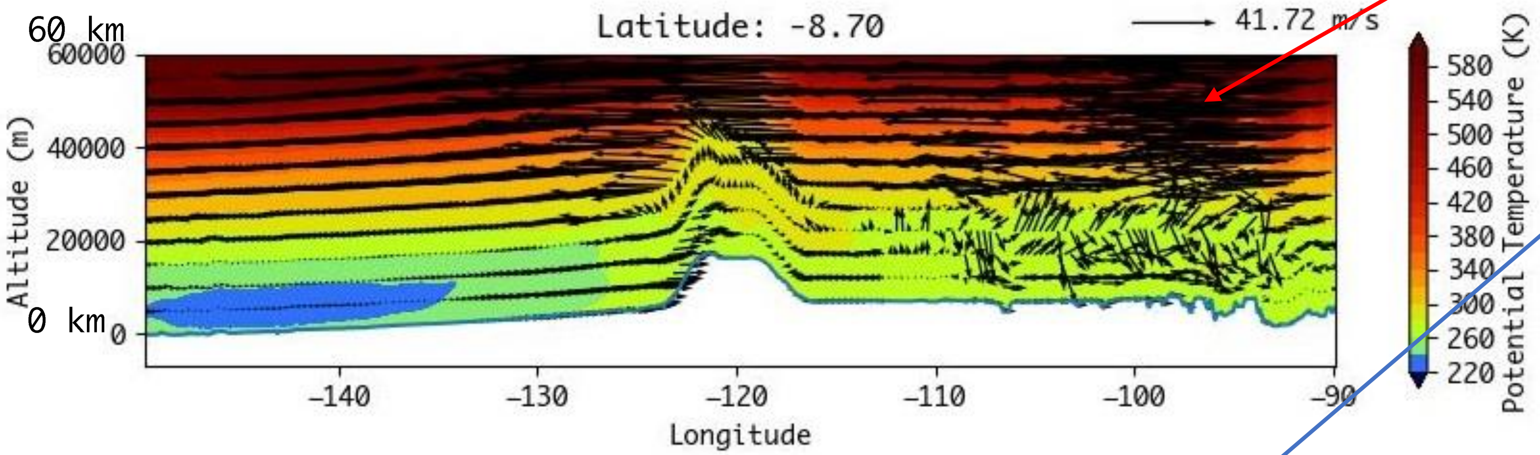
Simulated horizontal field
(30 km above surface)

Possible Causes:

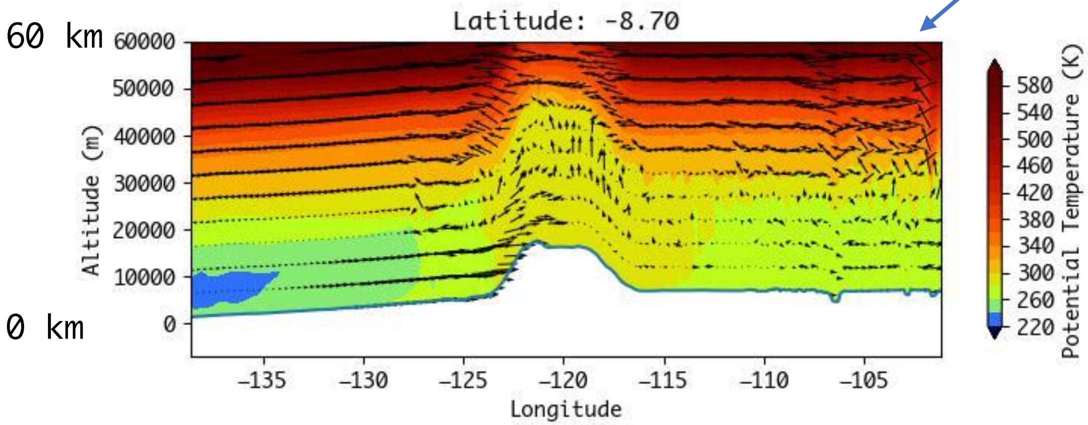
- Use of terrain-following coordinate system in steep topography.
- Vertical grid stretching, intricate pressure gradient computation, numerical instabilities in vertical velocity, and limitations in physical process representation.

Sensitivity to the Simulation Domain





↑ Arsia Mons in Tharsis Montes



← Isolated Arsia Mons (without Pavonis Mons)

The difference arises from the surrounding topography. Appropriate simulation domain should be carefully selected.

Summary

Findings from Idealized Simulation:

- The flat top surface of Arsia Mons enhances the updrafts.
- High background wind speeds are key for the updrafts, which also matches the AMEC season.
- High mountain altitude is also a key for strong updraft, a condition met by Arsia Mons.

Challenge from realistic Simulation:

- Influence of Tharsis Montes on Arsia Mons identified.
- Challenges with terrain-following coordinate system in steep terrain.

Future Work:

- To solve the challenges posed by Tharsis Montes' steep terrain in simulations.
- Understanding of AMEC Cloud Physics.