Large-eddy simulations of airflow dynamics and physics over the island of Graciosa

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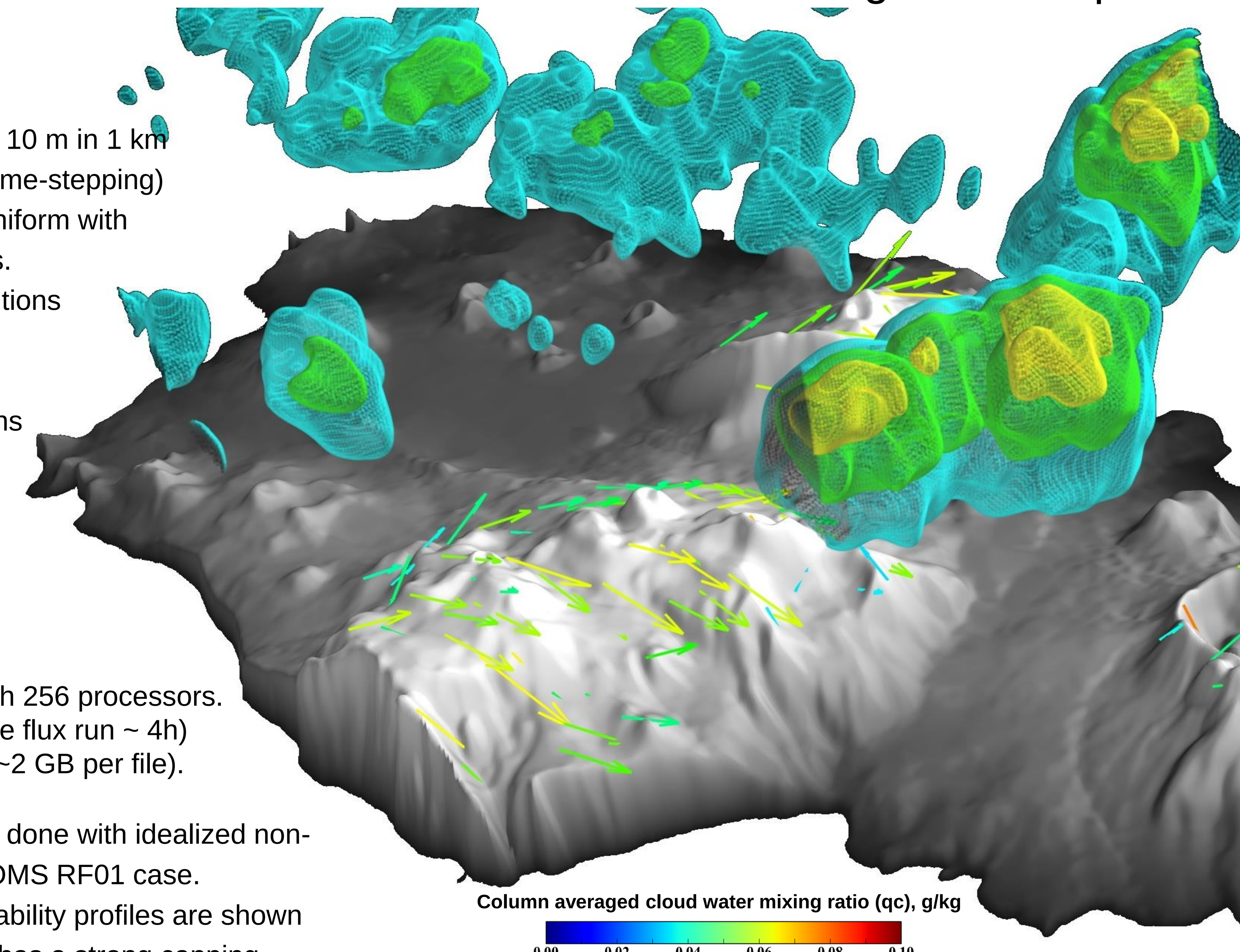
Three-dimensional Cloud Model 1 (CM1) experiments are performed to explore the mechanical and thermal impacts of Graciosa Island on the sampling of oceanic airflow and cloud evolution. The aim of the project is to create a modeling framework at true measurement resolutions to couple with cloud instrument simulators to investigate the impact of the terrain on observed cloud climatologies.

Moist simulation setup:

- Grid size: 12.8 x 12.8 x 1.5 km
- Δx, Δy = 20 m; Δz (stretched) = 10 m in 1 km
- Δt = 0.1 s (0.2 s with adaptive time-stepping)
- Initial wind profile is vertically uniform with the values of u = 7, v = -5.5 m/s.
- Doubly periodic boundary conditions
- Kessler microphysics
- Turbulence is initiated with [-0.1,0.1] K random perturbations in base theta field.
- Surface fluxes of heat and moisture are included.
- Monin-Obukhov theory based land-surface scheme.

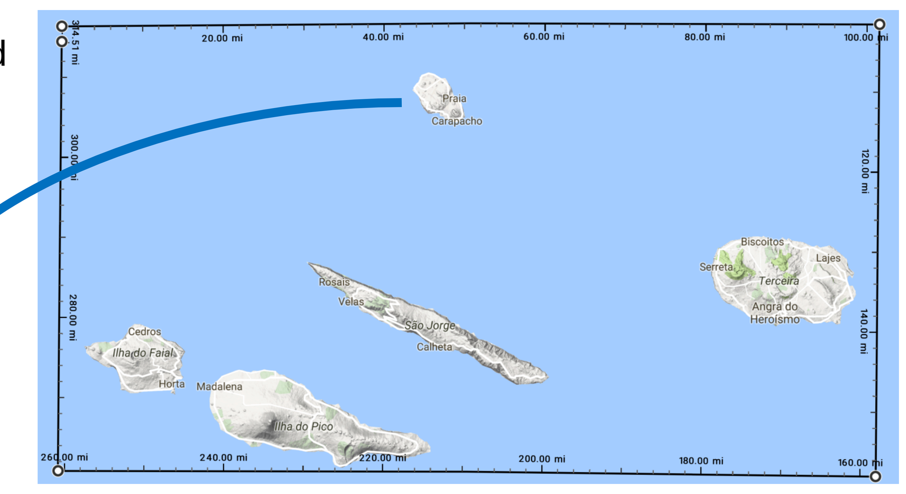
- 1 hour integration takes ~7h with 256 processors. (Open boundary and no surface flux run ~ 4h)
- Data output at every 10 mins (~2 GB per file).

- Single sounding initialization is done with idealized non-precipitating profile from DYCOMS RF01 case. Temperature, moisture, and stability profiles are shown below. Note that the sounding has a strong capping inversion(~10 K) at around 850 meters, which is conducive to development of marine stratocumulus below this level.



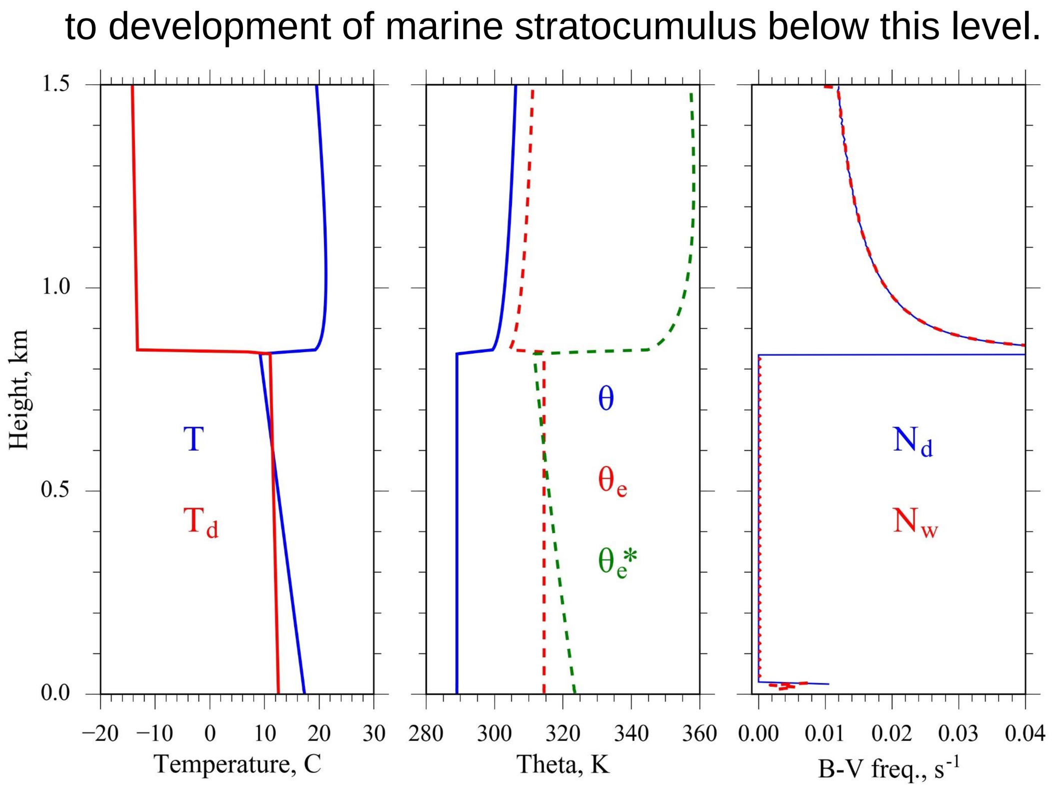
Terrain resolution: 20 meters. Based on the Shuttle Radar Topography Mission digital elevation data (courtesy of Nitin Bharadwaj of PNNL).

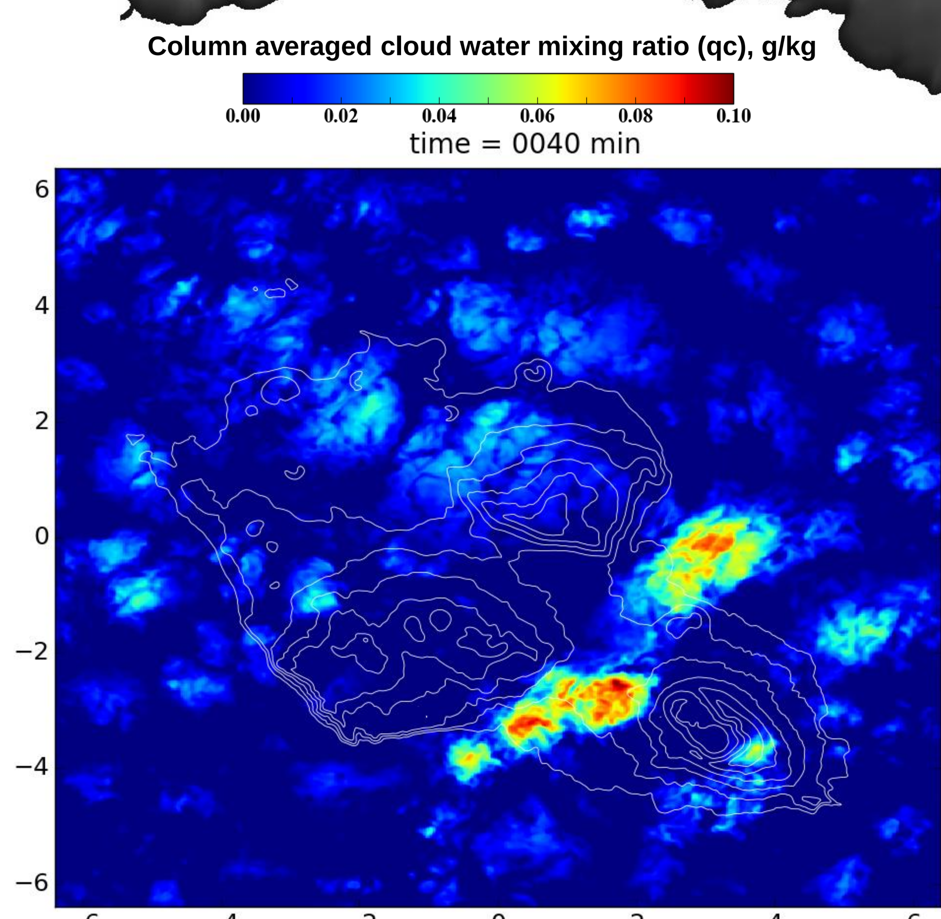
Terrain height in km:



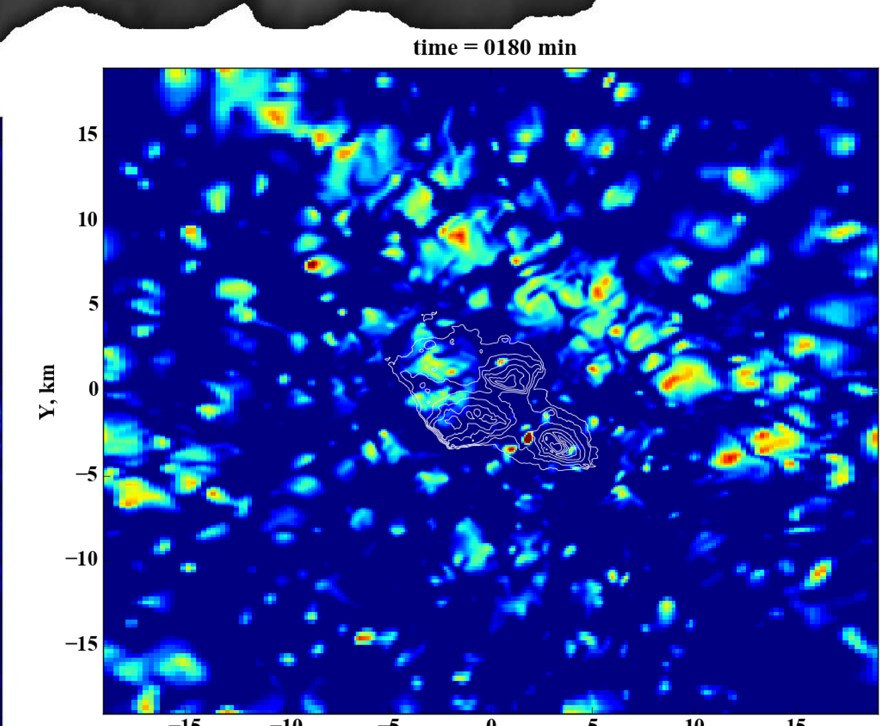
A terrain view from Google Maps showing 5 islands in the Azores region. Map area is approximately 150 x 100 km^2.

- 3D view of topography and iso-surfaces of cloud water mixing ratio (qc; 0-1 g/kg) along with select wind vectors at the surface at t = 40 min.
- CM1 employs a terrain-following grid system in the vertical which is reflected on the placement of wind field. The maximum upward motion (~wmax = 20 m/s) is located near the steepest upslopes as indicated from large vectors at the surface.
- The relatively deeper cloud layer over the island is produced as a result of mountain waves that are triggered by orographic forcing.

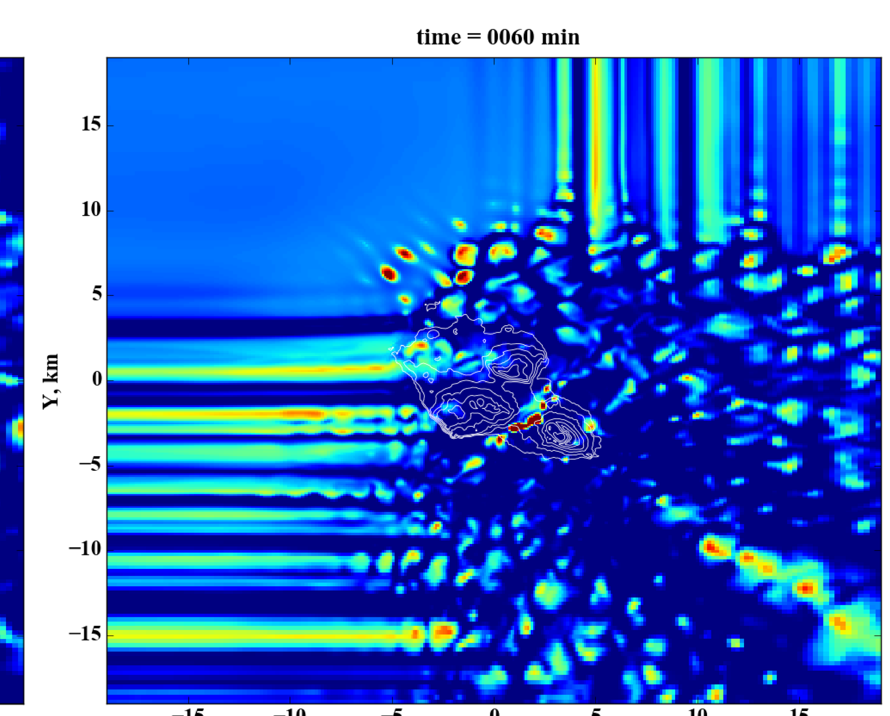




A top-down view of column averaged qc from the Δx, Δy = 20 m run showing ticker cloudy region near the caldera and alignments of clouds with steering wind.

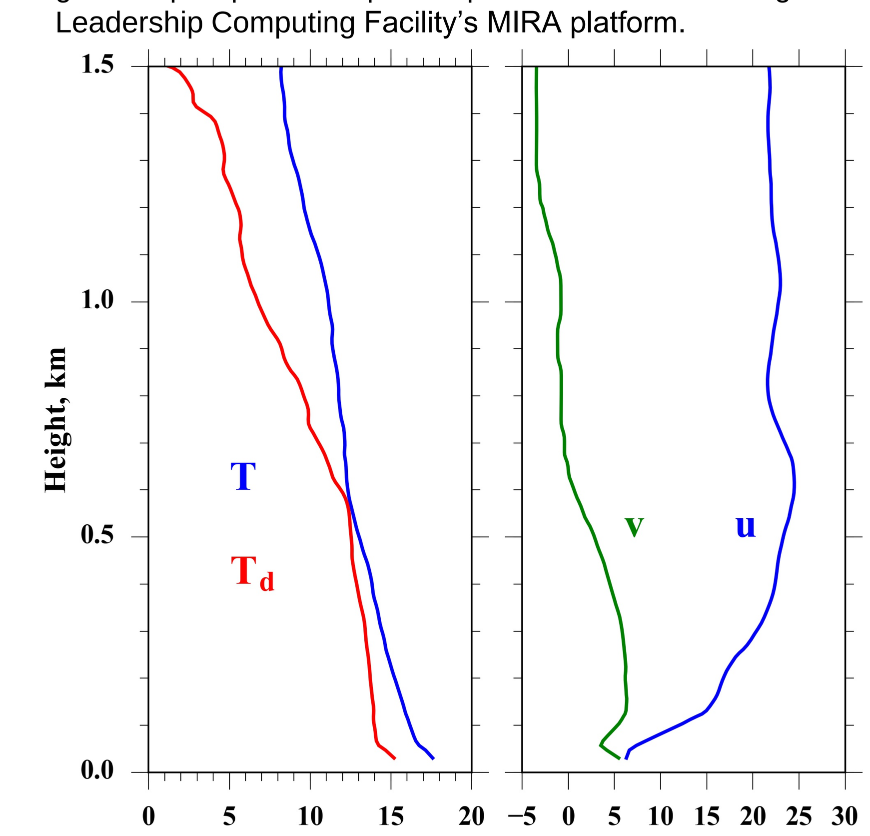


A snapshot of mean qc at t = 3h. Δx = Δy = 100 m; Δz = 20 m. Grid is stretched in three-dimensions. At this instance, perturbations downstream of the island nearly traverses the domain, which indicates how periodic boundary conditions impact upstream flow behavior. Additionally, without radiative effects the cloud field doesn't show any convective organization and the field is dominated by the island induced cumulus.

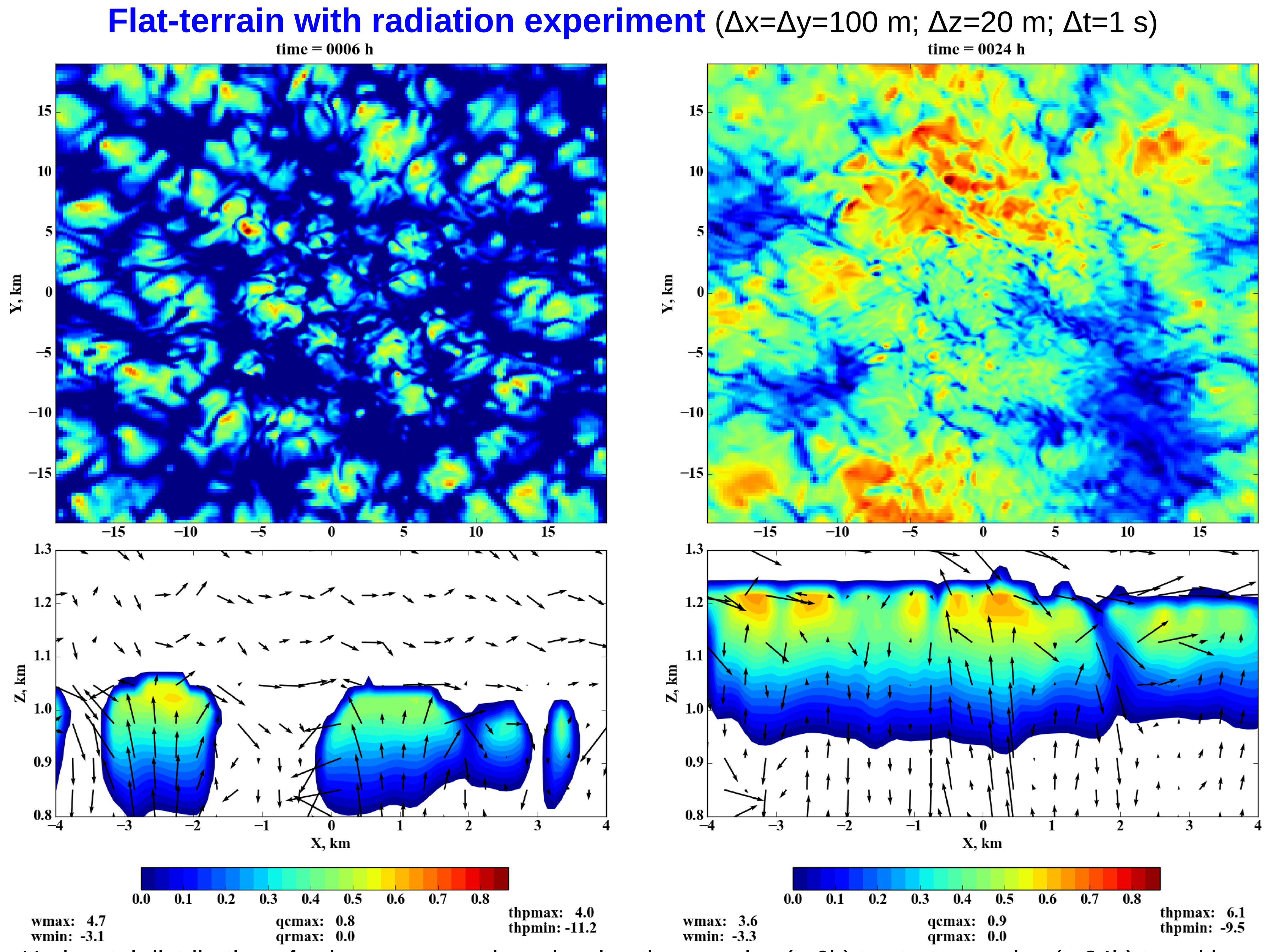


Same domain configuration except the boundary conditions are open in all directions. Upstream flow profile is severely impacted from the presence of the island.

12 UTC February 03, 2017 sounding from the ENA site. Note the high (> 20 m/s) westerly winds above the cloud base. Such large advection speeds worsen the viability of periodic boundary conditions in a relatively small single domain. A computational domain larger than 100 km might alleviate this problem, yet such grid setup requires a supercomputer on the scale of Argonne Leadership Computing Facility's MIRA platform.



Flat-terrain with radiation experiment (Δx=Δy=100 m; Δz=20 m; Δt=1 s)



- Horizontal distribution of column averaged qc showing the cumulus (t=6h) to stratocumulus (t=24h) transition at top panels. Cross-sections (at y=0) of qc show near 200 m growth of boundary layer between the snapshots along with the circulation patterns at bottom panels. Note that the system reaches to convective-radiative equilibrium at about 12 h as shown in the vertical profiles.
- Radiation scheme is based on NASA-Goddard longwave and shortwave radiation codes, initialized for 22 February 2017 at 19:30 and called at every 5 mins. (Skin temperature = 26 C). Morrison microphysics (double-moment) is used to explicitly resolve the cloud structure. Initial cloud droplet number concentration (Nd) is 100 cm^{-3}. A sensitivity simulation with Nd=250 cm^{-3} shows a relatively small change in boundary layer depth, which implies that flow dynamics dominates over microphysical processes.
- The equilibrium cloud field can be used as an input to terrain simulations to study the island effects further.

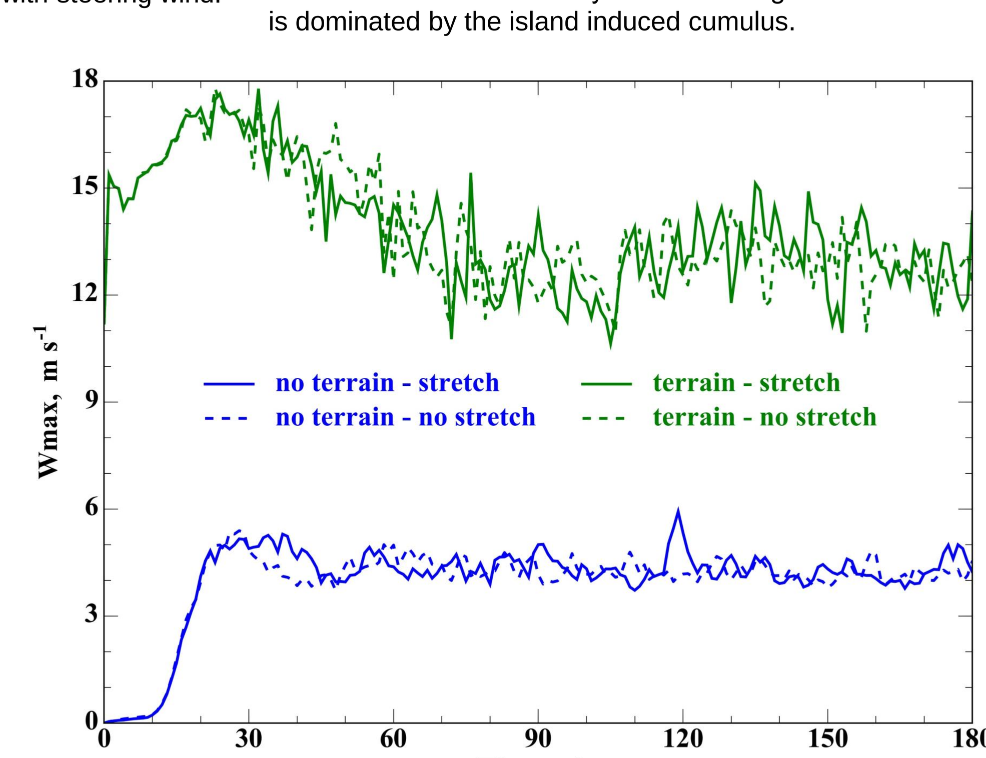
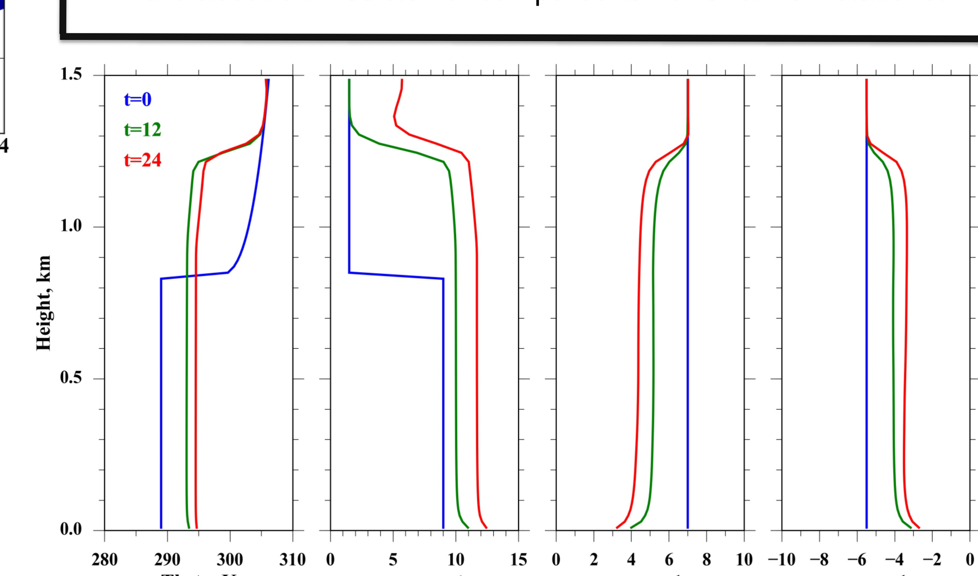
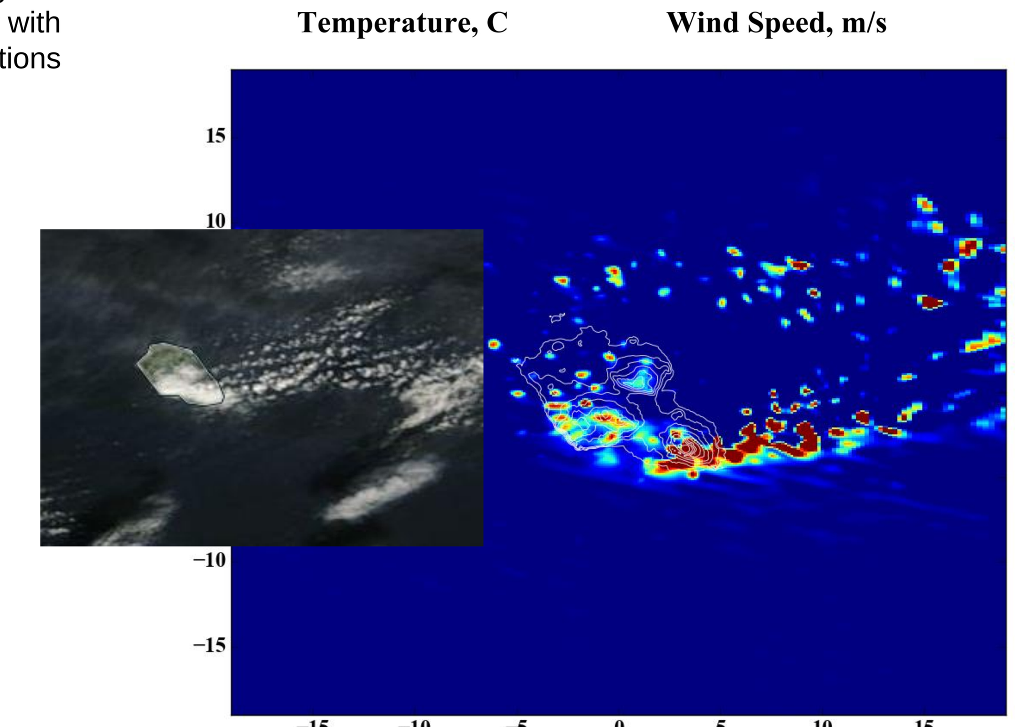


Figure shows the comparison of maximum updraft velocity (wmax) among terrain and no-terrain simulations with or without horizontal grid stretching option. Statistics are obtained throughout 3h runs. Terrain included simulations produce 2-3 times stronger updrafts as a result of orographic lifting. Since grid stretching does not impact the reliability of results, large-domain simulations can be performed more efficiently with 2X speed-up. With the current configuration, terrain enabled simulations are about 3 times slower compared to no-terrain simulations.



- Domain averaged vertical profiles of potential temperature, vapor mixing ratio (qv), and horizontal wind (u and v) at t = 0, 12, and 24 hours similar to Figs. 2&4 in Mechem et al, 2010; *Large-Eddy Simulation of Post-Cold-Frontal Continental Stratocumulus* (JAS).
- Overall, sub-cloud column is warmed and moistened; and kinetic energy is reduced as wind magnitude is lowered about a factor of two within 24h period. Note that, evident near the inversion transitions, the boundary layer growth is stabilized at 12 h into the simulation.



A preliminary simplified physics (Kessler microphysics and no-radiation) simulation result of average qc distribution over the island (t = 20 min). Visible satellite (MODIS/TERRA) image is included for comparison. Capturing the cloud street evolution requires further modifications in the model domain and settings.

This research is an ongoing effort towards the *Models to Observations: a Digital Atmospheric Library (MODAL)* project to bridge fine-scale modeling with remote sensing measurements of clouds and precipitation.

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