Improve Constrained Variational Analysis for Treatment of Sloping Terrain and LES Test on Shallow-Cumulus Clouds

$SH = \rho C_p \overline{w'\theta'}$

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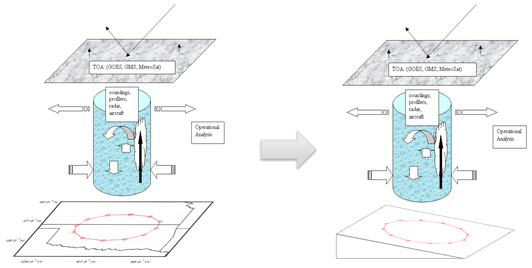
Motivation

- Constrained Variational Analysis (VARANAL) (Zhang and Lin 1997; Zhang et al., 2001) are currently designed for a cylinder atmospheric column assuming **flat surface** with constant pressure.
- Over the Great Plains region, **sloping terrain** is found to be crucial for LLJ dynamics and impact clouds and convective systems (Holton 1967; Parish and Oolman 2010; Fedorovich et al., 2017; Stelten et al., 2017; Reif and Bluestein 2018, Gebauer et al., 2018).
- How does the surface terrain impact the large-scale forcing derived from VARANAL and model simulations?

VARANAL in sigma-coordinate

pressure coordinate sigma coordinate



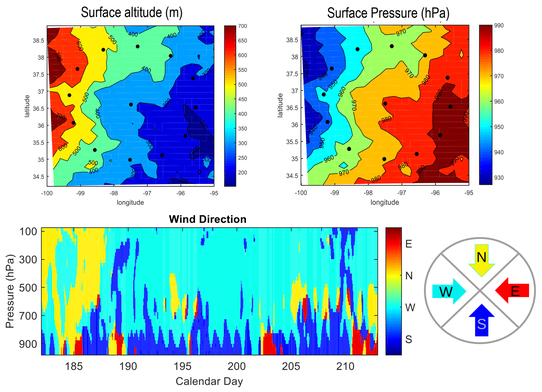
By changing the VARANAL algorithm from p-coordinate to σ-coordinate, the surface terrain along the column boundary is considered in the line integrals, therefore the fluxes and advections are calculated more accurately.

$$\frac{\partial \pi}{\partial t} + \int_0^1 \nabla_\sigma \cdot \left(\pi \overrightarrow{V_h}\right) d\sigma = 0 \qquad \sigma = \frac{p - p_T}{p_s - p_T} = \frac{p - p_T}{\pi}$$

$$\frac{1}{g}\int_0^1 \frac{\partial q\pi}{\partial t} d\sigma + \frac{1}{g}\int_0^1 \nabla_\sigma \cdot \left(\overrightarrow{V_h} q\pi\right) d\sigma - E + P + \frac{dql}{dt} = 0$$

$$\frac{1}{g}\int_0^1 \frac{\partial s\pi}{\partial t} d\sigma + \frac{1}{g}\int_0^1 \nabla_\sigma \cdot \left(\overrightarrow{V_h} s\pi\right) d\sigma - R_{TOA} + R_{srf} - LP - SH - L\frac{dql}{dt} = 0$$

Algorithm testing at SGP

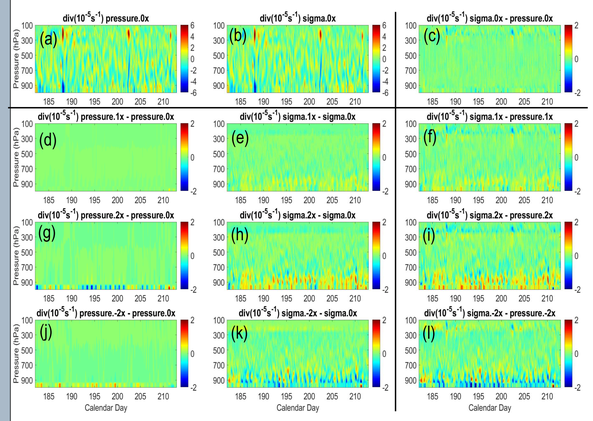


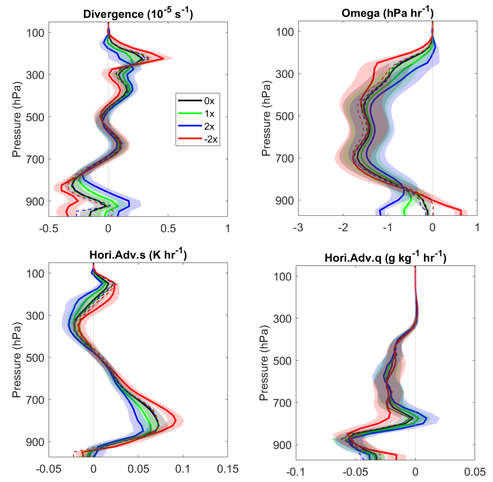
Lower-level upslope wind; upper-level downslope wind

Sensitivity of forcing to terrain

Setup of different slopes of terrain

Terrain	Description
0x	Surface heights at all boundary points equal to the domain-mean value
1x	Surface heights at all boundary points are the surface heights in reality
2x	The difference between surface heights and the domain-mean height is doubled
-2x	The difference between surface heights and the domain-mean height is doubled and reversed



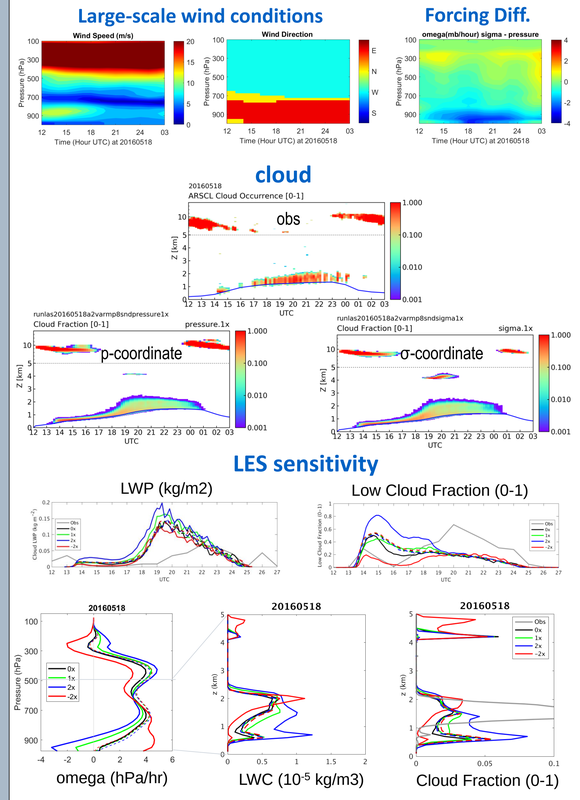


Dash: p-coordinate solid: σ-coordinate

1. Pressure-coordinate VARANAL is insensitive to terrain due to the flat-surface assumption.
2. Sigma-coordinate VARANAL is sensitive to terrain, especially in the lower-levels.
3. The terrain effect increases with slope, and opposite terrain has opposite effect.
4. Difference in omega and div in upper-level may be due to compensating effect to balance the constraints.
5. Terrain effects on horizontal advections are more prominent at levels with larger vertical gradient.

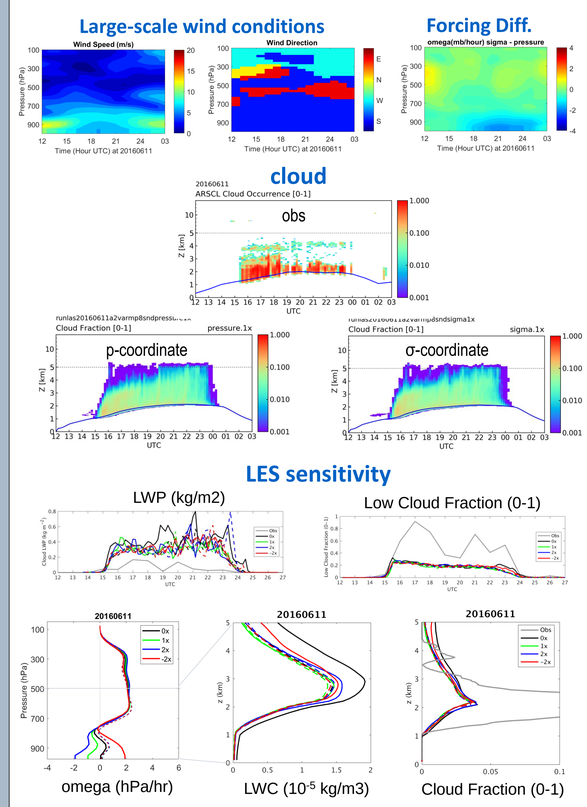
LES test on shallow-Cu clouds

20160518



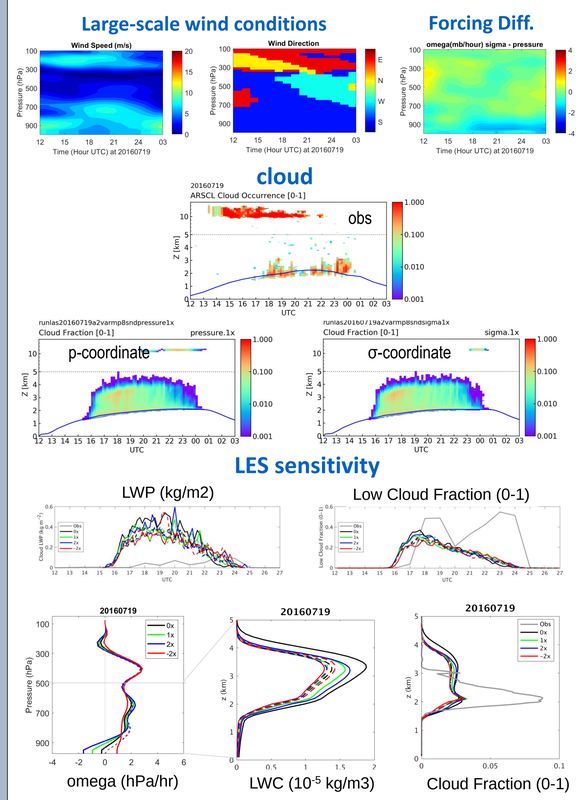
Clouds are impacted by the terrain-induced forcing change from sigma-coordinate VARANAL

20160611



LES test on shallow-cu clouds

20160719



For **20160518** case, clouds respond with terrain-induced forcing change.

- stronger upward motion in forcing → more shallow clouds in LES
- more prominent in morning time

For **20160611** and **20160719** cases, cloud are not linear responding to the terrain-induced forcing change.

- Forcing too weak? (weak cross-slope wind)
- Cloud base too high?

Summary

- The enhanced VARANAL in sigma coordinate captures the terrain effect that was not considered in the original algorithm.
- The terrain effect on the derived large-scale forcing increases with slope, and opposite terrain has opposite effect.
- The terrain-induced effect impacts the LES simulations of shallow cumulus clouds when the cross-slope wind is strong.
- Although the terrain effect on the large-scale forcing is relatively **small for SGP** site, it may have greater impact over other **steeper** region such as the **CACTI** field campaign.

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