Influences of Vertical Wind Shear on Updraft Accelerations in Simulated Convection

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BACKGROUND & MOTIVATION

- Convection that develops along the edges of cold pool boundaries is globally ubiquitous: It occurs over continents and oceans from the tropics to high latitudes. However, parameterization of convection in coarse-resolution numerical models is based largely on the thermodynamic structure of the atmosphere and little on the organization of convection or the dynamic structure (e.g., vertical wind shear) of the atmosphere.
- Characterize and classify forcing terms around precipitation – horizontal scaling of terms wrapped in the highest precipitation in relation to the edge of the cloud (providing a barrier from entrainment and dilution)
- The CALifornia Investigation of Convection over Ocean (CALICO) was a field experiment conducted in February – March 2022 in the Monterey Bay area to directly observe the thermodynamic and dynamic properties of convective updrafts in postfrontal convective regimes. At right is visible satellite imagery from one of the days during which convection was sampled, 5 Mar 2022. Convection mostly took the form of ~50 km wide arcs of convection that were driven by cold pools, with most of the convection occurring near the head of the cold pool.

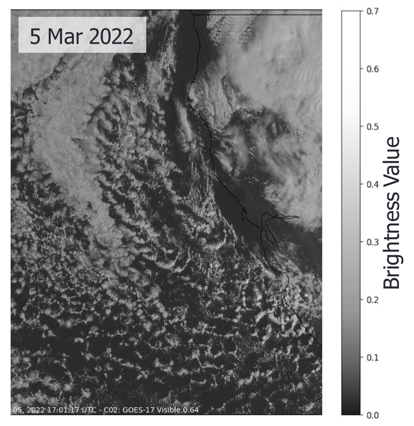


Fig. 1: GOES-17 Visible Imagery captured during the CALICO field experiment at 1701 UTC 5 Mar 2022

RESEARCH GOALS & QUESTIONS

Goals:

1. Evaluate data collected during CALICO alongside large eddy simulation (LES) model data using Cloud Model 1 to characterize forcing of cloudy updrafts within cold pool driven oceanic convection.
2. Determine which processes (thermodynamic vs. dynamic) are most responsible for updraft horizontal size, strength, and depth and whether boundary layer vs. free tropospheric atmospheric properties are more important.

Questions:

1. How does vertical wind shear impact updraft accelerations in isolated convection? How does this differ from updraft accelerations in cold pool driven convection?
2. Do atmospheric relative humidity and vertical wind shear affect updraft vertical accelerations by impacting updraft radius? What are the horizontal distributions of updraft accelerations within cloudy updrafts in various sheared environments? Does this horizontal distribution change when convection is organized along a cold pool instead of forming as an isolated element?

METHODS

- Cloud Model 1 (CM1) was used with 100 m grid spacing (horizontal and vertical) to simulate isolated convection forced by a +1 K, 1 km wide warm bubble at the center of a 10 km x 10 km domain and run for 1 hour. All simulations were forced with the thermodynamic profile seen at right. 4,000 parcel trajectories were initialized at model start at each grid point in the lowest 1 km of the model and within 1 km of the domain center.
- Simulations were run with various values of constant wind shear (S) between 0 and 6 km (surface to tropopause). Shown herein are results using S = 0, 1, and 2 m s^{-1} km^{-1}.

$$\frac{Dw}{Dt} = -\frac{1}{\rho_o}\frac{dp'}{dz} + B = -\frac{1}{\rho_o}\frac{dp_{D,NL}}{dz} - \frac{1}{\rho_o}\frac{dp_{D,L}}{dz} - \frac{1}{\rho_o}\frac{dp_B}{dz} + g\frac{\rho'}{\rho_o}$$

Nonlinear Dynamic PGA — Linear Dynamic PGA — Effective buoyancy

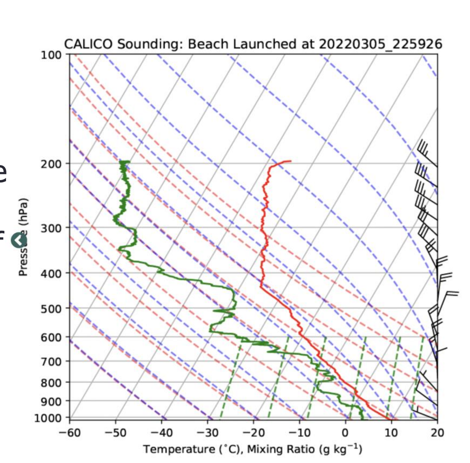


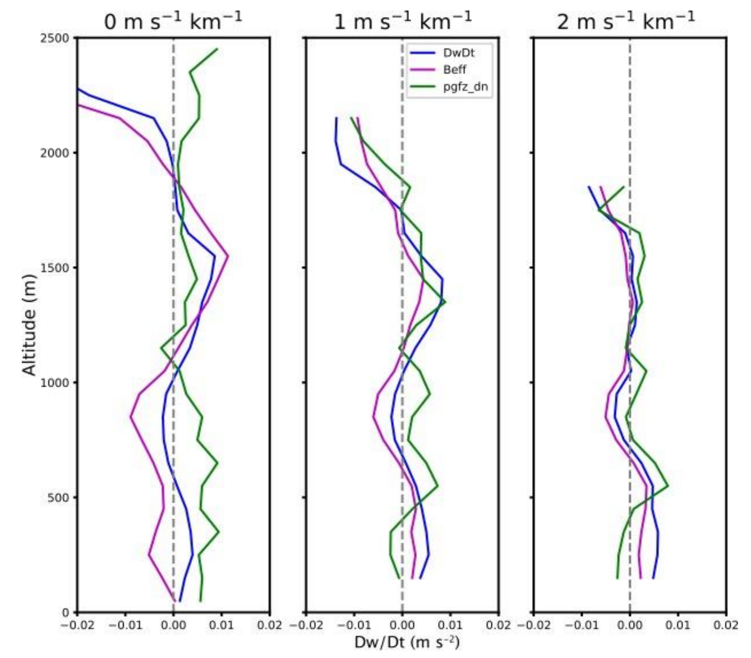
Fig. 2: Rawinsonde launched during CALICO at 2259 UTC 5 Mar 2022 from Monterey, CA.

1. Input observed soundings from CALICO into CM1 to first simulate idealized isolated convection
2. Conduct sensitivity tests by altering vertical wind shear, using constant shear values of 0, 1, and 2 m s^{-1} km^{-1}
3. Evaluate vertical profiles of effective buoyancy, pressure gradient accelerations and updraft size
4. (Ongoing) Compare warm bubble simulation to updrafts along a cold pool using the same sounding data from 5 Mar 2022

RESULTS

- The convection reaches ~3 km altitude for S = 0 m s^{-1} km^{-1}, 2.6 km for S = 1 m s^{-1} km^{-1}, and 2.3 km for S = 2 m s^{-1} km^{-1}.
- With S = 0 m s^{-1} km^{-1}, effective buoyancy was positive at 1.1–1.8 km, reaching about 0.01 m s^{-2} at 1.6 km. The dynamic PGA below 1.1 km in the S = 0 m s^{-1} km^{-1} simulation was positive.
- Overall total acceleration (blue) closely mirrored that of effective buoyancy.

Fig. 3 (right): Composite vertical profiles of effective buoyancy (Beff; magenta), dynamic nonlinear PGA (pgfz_dn; green), and total vertical acceleration (Dw/Dt; blue) for the 400 highest reaching parcels for each value of S.



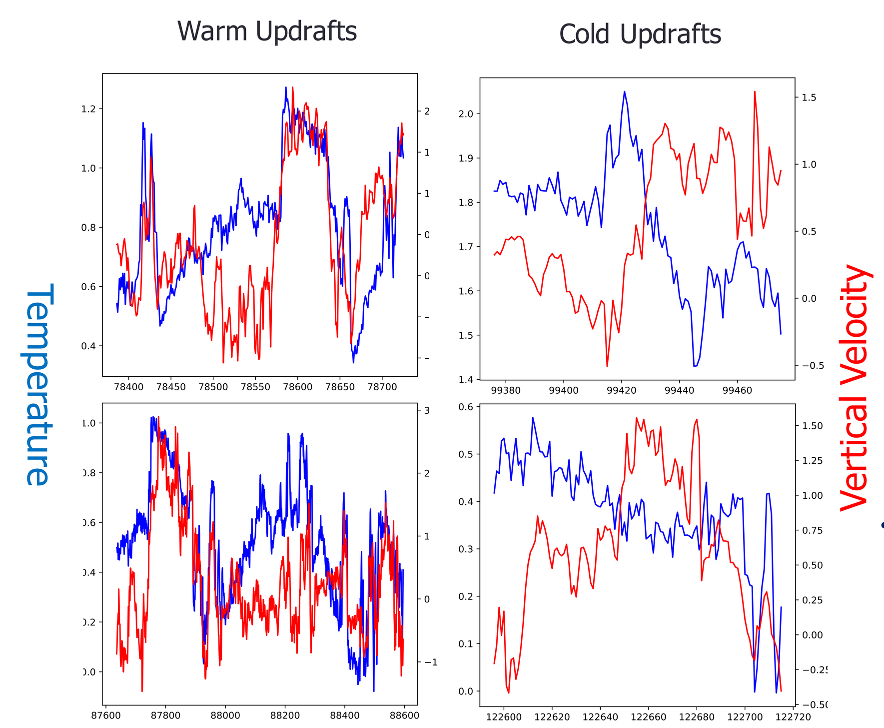
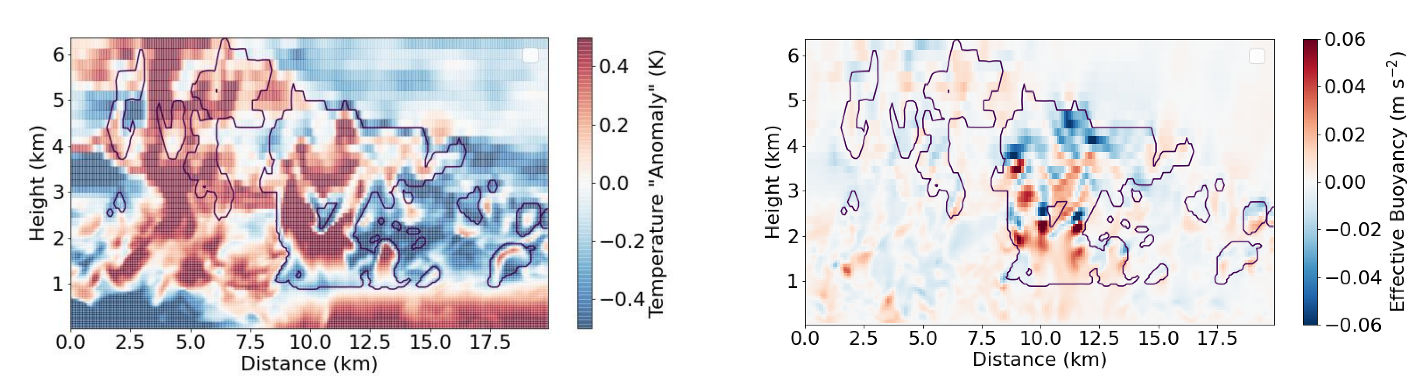


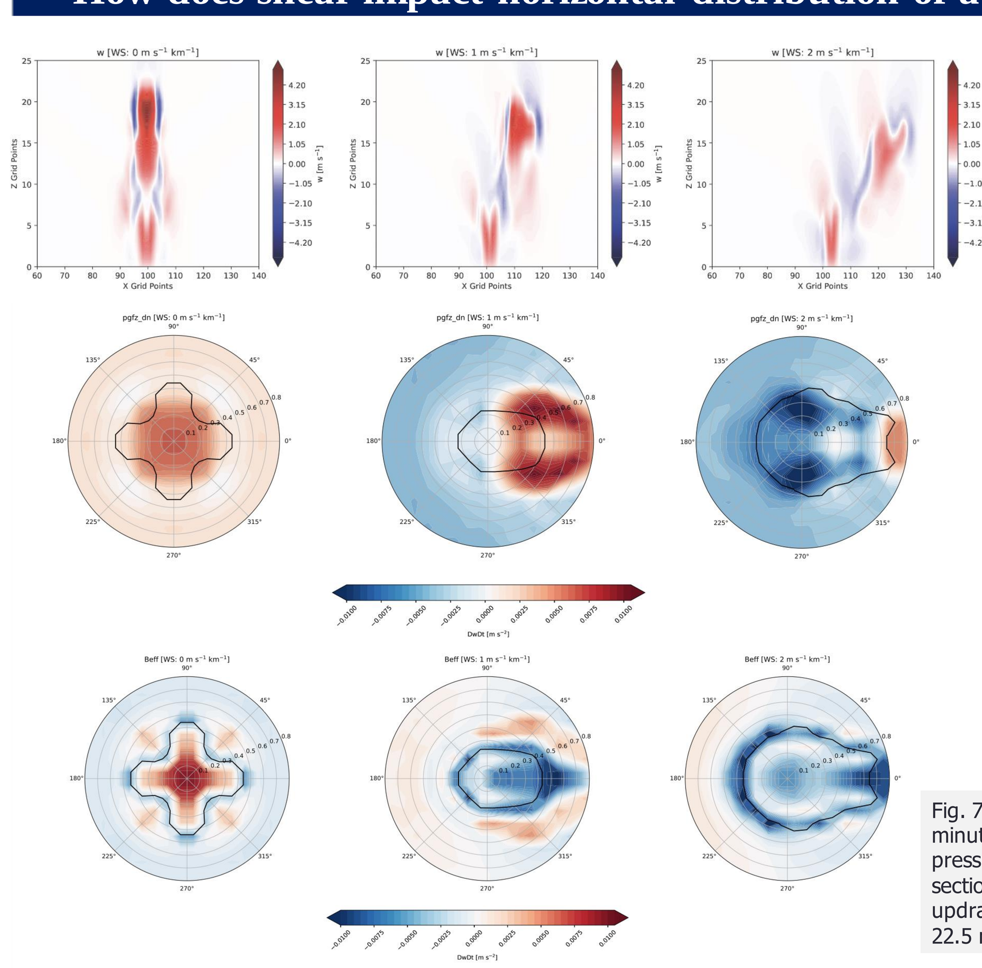
Fig. 4 (left): Time series of in-cloud temperature (blue) and vertical velocity (red) measured by the NPS Twin Otter aircraft on 5 Mar 2022. The left column shows two examples of updrafts where temperature increased at the same time and location as vertical velocity. The right column illustrates temperature and vertical motion in "cold" updrafts, where updrafts exceeding 1 m s^{-1} occurred where the temperature was colder than surrounding air.

Figs. 5, 6 (below): Cross-sections through a CM1 simulation forced with the sounding in Fig. 2 but initialized with random potential temperature perturbations of up to 0.25 K in the boundary layer. Cross-sections were taken after a single cold pool driven convective line had developed in the model. Bottom left: Temperature relative to average temperature at each height level. Bottom right: Effective buoyancy. Black lines outline clouds.

- The base of the cloud between 7.5 and 12.5 km on the x-axis contained cold temperature anomalies; however, it still contained an upward pressure gradient acceleration that exceeded the negative Archimedean acceleration.



How does shear impact horizontal distribution of acceleration within updrafts?



Key Takeaways

Increased magnitudes of shear yield:

- Decrease in vertical velocity within the cloud core
- Increase in pressure gradient acceleration downshear of the defined cloud radius
- Decrease in effective buoyancy within the updraft core (correlating to weaker vertical velocity)

Fig. 7: (top) Vertical cross section of vertical velocity at 22.5 minutes. (middle) Horizontal cross sections of dynamic pressure gradient acceleration. (bottom) Horizontal cross sections of effective buoyancy relative to the maximum updraft vertical velocity. Polar plots at 1.5 km altitude and 22.5 minutes after model initialization.

ONGOING WORK

Cold Pool Comparison

- Insert and analyze parcel trajectories in CM1 simulations that produce convection organized along cold pool boundaries.
- Why are these convective elements able to reach the tropopause even though the shear was close to 2 m s^{-1} km^{-1}? Does reducing the shear affect the development of cold pools?

Cold Pool Hypotheses: Moisture Preconditioning

- Horizontal scaling of updraft acceleration (shading), vertical velocity, and temperature with cloud top height, corresponding to similar distribution and/or length scales centered around the leading edge of the cold pool.
- Correlation between local areas of increased rain rate, negative dynamic pressure gradient acceleration (PGA) terms and the distance to the leading edge of the cold pool.
- Cold pool simulations will show stronger values of PGA correlating with liquid water path due to increased magnitudes of shear, and overall, an environment that will initiate and sustain deeper convection.

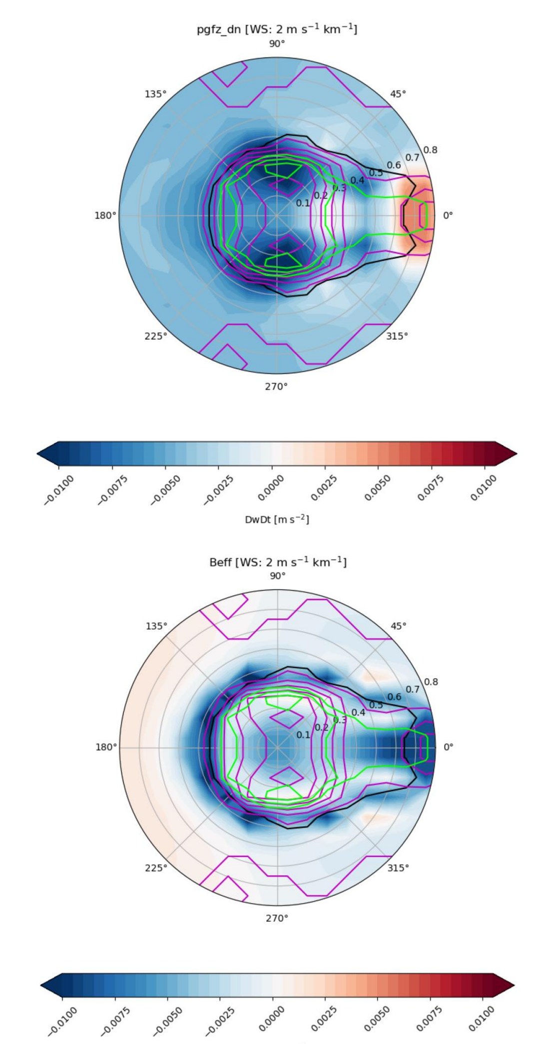


Fig. 8: Horizontal cross sections of pgfz_dn and Beff from warm bubble simulations, relative to the maximum updraft vertical velocity. Contours of liquid water path (LWP; magenta) and vertical velocity (w; green). Polar plots at 1.5 km altitude and 22.5 minutes after model initialization.

CONCLUSIONS

1. For isolated updrafts, vertical wind shear appears to reduce the maximum height of updrafts (similar to Peters et al. 2022a,b).
2. However, in convection organized along a cold pool in a highly sheared environment, convection was able to reach the tropopause (not shown).
3. Updrafts that were colder than the immediate environment were observed during CALICO. Such updrafts also appear in CM1. Though not shown here, the "cold" updrafts in CM1 have similar size distributions, frequency of occurrence, and temperature anomaly magnitudes as those observed. This further supports the notion that vertical pressure gradient accelerations, including dynamic terms that may be impacted directly by shear, may need to be considered in cumulus parameterizations—not just thermodynamic properties of the atmosphere.

Peters, Morrison, H., Nelson, T. C., Marquis, J. N., Mulholland, J. P., & Nowotarski, C. J. (2022). The Influence of Shear on Deep Convection Initiation. Part I: Theory. *Journal of the Atmospheric Sciences*, *79*(6), 1669–1690. https://doi.org/10.1175/JAS-D-21-0145.1

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