11C.7 INITIATION OF OROGRAPHIC MOIST CONVECTION IN THE TROPICS

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1. INTRODUCTION

A simple orographic lifting situation of a conditionally unstable atmosphere provides an opportunity to isolate and identify different convective triggering mechanisms. There are two basic methods for generating convection with this background state. The first is non-uniform lifting, and the second is uniform lifting of a nonhomogeneous atmosphere.

Both methods have been explored through numerical modeling. Miglietta and Rotunno (2009) used small smoothed terrain variations to break the y-symmetry of their model without producing stationary features. Fuhrer and Schar (2004) instead used random small-scale temperature perturbations in the upstream environment. The two methods were combined by Kirshbaum and Durran (2005a). They varied the roughness of the terrain and compared the rain produced in each case with and without thermal inhomogeneities.

While modeling is relatively new, the idea of triggering convection is not. Since the 1960s, it has been thought that variations in the upstream atmosphere could lead to rain and convection over islands (Woodcock, 1960). Modeling is the most common and powerful way to test the two mechanisms. However, it is often not realistic and great care needs to be taken with the magnitude and location of convective triggering because they can strongly modify results.

Non-uniform lifting and uniform lifting of a nonhomogeneous atmosphere will both act to seed convective cells. When using observational data, only theory and experiments with a nonhomogeneous atmosphere are possible. While both methods for generating convection are equally probable and likely work in tandem in the real atmosphere, this study will focus on using observational data to investigate the second method of uniform lifting in a nonhomogeneous atmosphere.

2. DATA SET & KEY QUESTIONS

Observational data from the field phase of the DOMEX (Dominica Experiment) project has been used to test our hypotheses of triggered moist convection. The project centered on the Commonwealth of Dominica, a small island in the trade wind belt (15°N, 61°W) shown in Figure 1. Its mountainous peaks extend above the lifting condensation level (LCL) but below the trade-wind inversion. Lifting of conditionally unstable air by the windward slopes initiates new convection and enhances already existing convection incoming with the trade wind flow (Kirshbaum and Smith 2009, and Smith et al. 2009). These conditions make Dominica an ideal place to study the triggering of moist convection. In-situ measurements around Dominica from 21 fixed research flight tracks by the Wyoming King Air aircraft along with fixed observational platforms allow us to focus on a few key questions.

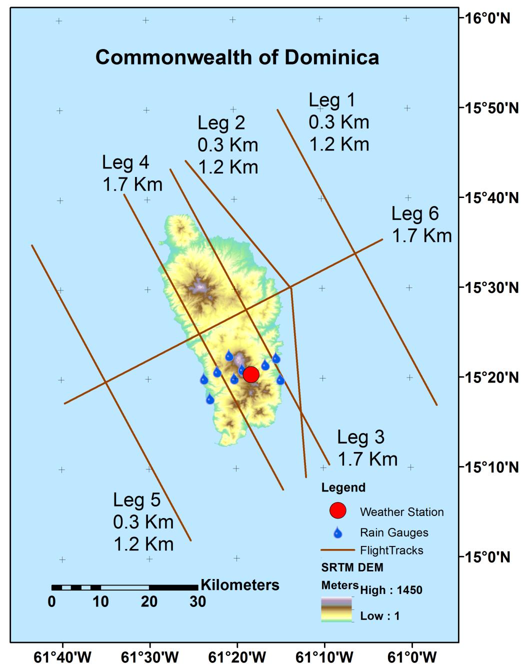

Figure 1: A map of Dominica showing flight tracks along with terrain height and instrument locations.

1. How do “seeds” in the upstream environment trigger convection over the island?

2. How is differential buoyancy produced, and how does it generate vertical accelerations?

3. Are the properties of the upstream environment, when combined with uplift, enough to produce the observed over-island convection?

3. NEUTRAL BUOYANCY SEEDS

The inhomogeneous tropical Atlantic atmosphere was carefully observed in the DOMEX field campaign. An upstream flight track shown as “Leg 1” in Figure 1 was located 30 km East of Dominica’s long axis, 300

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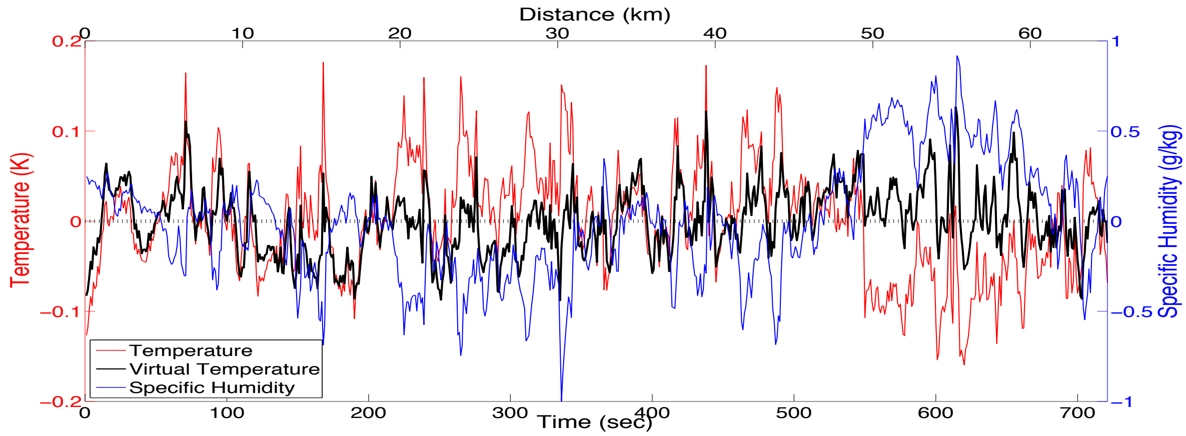

Figure 2: Variations of Temperature (T) and Specific Humidity (Q) along Leg 1L of a research flight. T and Q are anti-correlated such that the Virtual Temperature (Tv), a function of both variables, is nearly zero.

m high, and 70 km long. It provided an ideal view of the perturbations in moisture (Q), but also temperature (T) in the subcloud layer before the layer is orographically lifted. We found that the upstream T and Q perturbations balance each other such that they maintain a near constant virtual temperature (Tv), often called a density temperature. The equation for Tv is shown below where Q_v is water vapor mixing ratio, and Q_l is liquid water mixing ratio. Because the flight track is in the subcloud layer, Q_l is almost always zero.

$$T_v = T(1 + 0.61Q_v - Q_l) \tag{1}$$

Regions within the layer are either warm and dry, or cool and moist. By having constant Tv, the layer has neutral buoyancy. We call these neutral buoyancy patches "seeds" because they are passive in the upstream environment but upon orographic uplift by the island, they seed convection. Figure 2 shows a flight track with T and Q balanced such that a near constant Tv is achieved. On average, T and Q are anti-correlated with a correlation coefficient of -0.8 when not influenced by rain. Figure 3 shows T and Q perturbations for a typical research flight. Notice how the perturbations scatter around a slope of constant Tv.

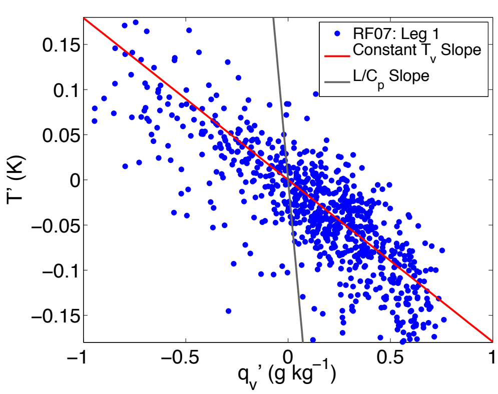

Figure 3: Scatter diagram of T and Q perturbations along Leg 1L of a research flight. The perturbations scatter along a line of constant Virtual Temperature (Tv) rather than along L/Cp.

Neutral buoyancy seeds are a variation of the temperature perturbations used to trigger numerically modeled convection. Instead of slightly modifying the T field, which immediately creates instabilities in the upstream flow, one could modify both the T and Q fields of a model in a balanced way to keep the same stability. In theory, no convection would be induced until the region was activated upon uplift.

In the real atmosphere, complex convective processes can create a variety of T and Q perturbations. The usual description involves turbulent entrainment of potentially warm dry air at the top of a mixed layer. In contrast, evaporation of falling rain might create cool moist patches (Paluch and Lenschow, 1991). The neutral buoyancy regions are likely produced through buoyancy sorting where these parcels with various properties shift vertically until they're balanced. While turbulent mixing erodes the edges of the patches, new air is continuously added as parcels traverse the Atlantic. The seeds remain as passive tracers in the flow until they become activated.

4. SEED ACTIVATION

Seeds become activated through uplift, orographic or otherwise. In the case of Dominica, we hypothesize that seeds are activated in a two-step process. As the upstream low-level air encounters the island, the first step is laminar lifting whereby the entire layer is uniformly elevated. When lifted, some air parcels generate relative buoyancy with respect to others due to the presence of seeds (Woodcock, 1960). The relatively cool but moist parcels reach their LCL first and begin to generate positive buoyancy with respect to other drier parcels that have not reached saturation and are still decreasing in T by the dry adiabatic lapse rate.

The second step of the seed activation process begins when parcels have gained enough buoyancy to lift out of the layer, and lift further still into the environment. Using a high pass filter, we analyzed the amount of relative buoyancy produced through the stages of uplift. We found a threshold value for the buoyancy necessary to transition from a laminar flow regime to plume convection. The parcels that pass the buoyancy threshold have the potential to initiate larger plumes of convection. However, their ability to do so depends on their buoyancy with respect to the environmental air above their layer and along their lifting path.

5. LIFTING METHOD

A simple lifting method was used to better understanding the transition from laminar flow to plume convection. This allows for an observational analysis of the second method described for generating convection in a conditionally unstable atmosphere; uniform uplift of a nonhomogeneous atmosphere. Using this method, the changes in acceleration as the laminar layer lifts can be calculated.

Each parcel measured along the upstream aircraft track was lifted step by step pseudoadiabatically. The calculation is begun with the variables T, Q_v, Q_l, and pressure (P) measured by the Wyoming King Air. Along the lifted path, Tv from equation 1, and a parcel's vertical acceleration (w_t) are calculated and tracked.

$$w_t = g\frac{T_v{}'}{\bar{T}_v} \tag{2}$$

The vertical acceleration at each step helps to explain how the layer develops with lifting.

6. ACCELERATION FILTER

In order to remove false vertical accelerations associated with large-scale buoyancy variations in the data, a high pass Fourier filter was used. With the linearized 2-D Euler and continuity equations, the vertical accelerations (w_t) can be found through the following partial differential equation.

$$\bar{\rho}(w_{zz} + w_{xx})_t = -g\rho'_{xx} \tag{3}$$

We assume the flight level data is representative of a layer of depth H with variable density in the horizontal, embedded in a deep uniform density above and below as pictured in Figure 4.

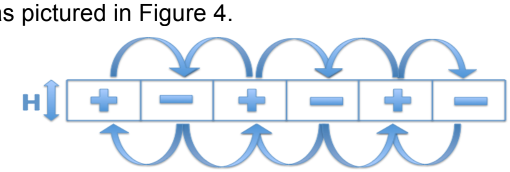

Figure 4: Schematic of density variations in a layer depth, H, as measured by an aircraft.

This assumption yields the following solution for the vertical acceleration (w_t) in Fourier space.

$$\hat{\dot{w}}(k) = -\left(\frac{g}{\bar{\rho}}\right)\hat{\rho}\left[1 - \exp\left(-\frac{kH}{2}\right)\right] \tag{4}$$

According to this formula, short wavelength density anomalies with kH>>1 accelerate quickly according to the reduced gravity formula.

$$\hat{\dot{w}}(k) = -\left(\frac{g}{\bar{\rho}}\right)\hat{\rho} \tag{5}$$

Longer wave density anomalies accelerate more slowly due to the lateral circulations that must develop to allow parcels to rise. This reduction in vertical acceleration is often called the added mass effect. This high-pass filter in Fourier space removes any non-physical accelerations from density anomalies with horizontal scale larger than the vertical scale. We chose H=1 km as the vertical layer depth for the density variations. An example of this filter is shown in Figure 5. Notice how large-scale variations are damped while small-scale variations are maintained.

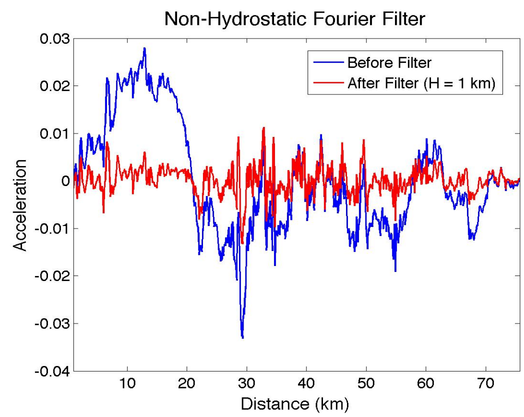

Figure 5: The effects of applying the non-hydrostatic Fourier filter with a layer depth H=1 km to the accelerations calculated along an aircraft leg.

7. DIFFERENTIAL ACCELERATION

The lifting method and acceleration filter are both steps towards determining how much acceleration an individual air parcel feels relative to the parcels that surround it. Without enough acceleration, parcels will not be pushed out of the laminar flow and thus plume convection will not commence.

The standard deviation (σ) of vertical acceleration is a useful quantity for this purpose. At each lifting step, the data is filtered and the standard deviation is calculated. The growth in the standard deviation of acceleration for a collection of research flights is shown in Figure 6. The initial value of $\sigma(w_t)$ is highly dependent on the initial variations in T at flight level, but also the correlation strength between T and Q. If T and Q are strongly anti-correlated, the initial $\sigma(w_t)$ will be small. As the layer is lifted and parcels reach their LCL, $\sigma(w_t)$ grows. The final value of $\sigma(w_t)$ depends on variations in Q which determine how much lifting is required for all parcels to reach their LCL. While variations exist between flights, all show buoyancy increasing with uplift.

If a threshold value of vertical acceleration is reached within the advective time scale, parcels will leave the laminar layer and begin plumes. We use a scaling argument to determine the acceleration necessary for this transition to occur. If acceleration (a) is maintained for some time (t) the vertical displacement is given by the following classic equation.

$$d = \left(\frac{1}{2}\right)at^2 \tag{6}$$

After solving for acceleration, the threshold value is then given by the required parcel displacement and the time available.

The time scale in our problem is well defined. Parcels need time to produce buoyant plumes on the windward side of Dominica before they are damped through descent on the lee side. The advective time scale is thus the distance traveled (L) over the wind speed (U).

$$T_{advec} = \frac{L}{U} \quad (7)$$

L is estimating to be 4 km, which is about a quarter of the island width. The initiation needs to occur early such that time is still available for convection to develop. The average wind speed is 7 m/s, allowing less than 10 min for the laminar flow transition to plume convection.

The vertical displacement (d) is less constrained. This is the vertical distance a parcel must travel before it can be considered outside of its layer, and accelerating through the environment. We choose two potential vertical displacement, d=300 m and d=500 m. The threshold acceleration needed for the transition to plume convection in these two cases is 0.0018 ms^{-2} and 0.0031 ms^{-2} as shown in Figure 6. The results depend on the choice of d, but both are in a plausible range to trigger convection.

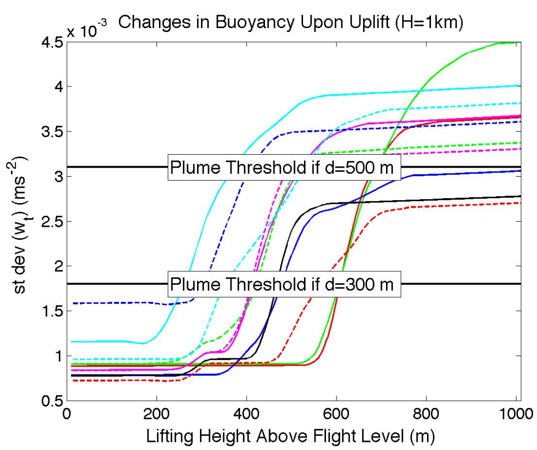

Figure 6: Increases in differential acceleration with uniform uplift of seeds. A subset of 12 research flights are plotted to show daily variations. The acceleration threshold to move from laminar layer lift to plume convection for two values of displacement is shown.

The amount of uniform lifting of low-level air to reach the estimated threshold is between about 300-600 m above the flight level at 300 m. This is also in an appropriate range given that along its spine, Dominica's terrain ranges from 600 m in the saddle to about 1,400 m at the two peaks.

8. CONCLUSION

With a combination of observational data from aircraft, together with theory, we tested the hypothesis that uniform lifting of a non-uniform atmosphere can generate convection over Dominica.

Using aircraft data from the DOMEX field campaign, anti-correlated patches of T and Q were found in the upstream air. We hypothesize that these neutral buoyancy seeds are activated upon uplift to produce the convection found over Dominica. Using a lifting method and non-hydrostatically corrected data, we calculated the amount of differential acceleration produced through uniform layer uplift. A threshold value of acceleration was found and we hypothesize that once this value is reached, parcels will leave their layer and have the potential to begin plume convection in the environment. This transition from laminar lifting to plume buoyancy is the initiation of convection.

The calculations described only take into account the first step of the seed activation process. Once parcels leave their layer the buoyancy of each lifted parcel with respect to the environment must be taken into consideration. Future work will explore this question along with the second method for generating convection, non-uniform lifting. The lifting method will be extended to track parcels after they enter the environment while T and Q seeds will be added to a model to seed convection. Using realistic terrain in the model domain will also help to see the role of the terrain in triggering convection.

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