Response of Atmospheric Convection to Vertical Wind Shear: Cloud-System Resolving Simulations with Parameterized Large-Scale Circulation.

Part I: Specified Radiative Cooling.

Usama Anber$^{1,3}$, Shuguang Wang$^2$, and Adam Sobel $^{1,2,3}$

1 Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY
2 Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY
3 Department of Earth and Environmental Sciences, Columbia University, New York, NY

Corresponding Author: Usama Anber, Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964. E-mail: uanber@ldeo.columbia.edu
ABSTRACT

It is well known that vertical wind shear can organize deep convective systems and greatly extend their lifetimes. We know much less about the influence of shear on the bulk properties of tropical convection in statistical equilibrium. To address the latter question, the authors present a series of cloud-resolving simulations on a doubly periodic domain with parameterized large scale dynamics based on the Weak Temperature Gradient (WTG) approximation. The horizontal mean horizontal wind is relaxed strongly in these simulations towards a simple unidirectional linear vertical shear profile in the troposphere. The strength and depth of the shear layer are varied as control parameters. Surface enthalpy fluxes are prescribed.

The results fall in two distinct regimes. For weak wind shear, time-averaged rainfall decreases with shear and convection remains disorganized. For larger wind shear, rainfall increases with shear, as convection becomes organized into linear mesoscale systems. This non-monotonic dependence of rainfall on shear is observed when the imposed surface fluxes are moderate. For larger surface fluxes, convection in the unsheared basic state is already strongly organized, but increasing wind shear still leads to increasing rainfall. In addition to surface rainfall, the impacts of shear on the parameterized large-scale vertical velocity, convective mass fluxes, cloud fraction, and momentum transport are also discussed.
1. Introduction

Environmental wind shear can organize atmospheric moist convection into structures that contain mesoscale motions with a range of horizontal scales, from a few kilometers to thousands of kilometers. Severe convective storms, supercells, squall lines, mesoscale convective systems (MCS), tropical cloud clusters, trade cumulus, tropical cyclones, and the Madden-Julian Oscillation are all influenced by wind shear, in various ways (e.g., Cotton and Anthes 1989; Houze 1993). Understanding the role of the vertical wind shear in the formation of thunderstorms, squall lines and other mesoscale features has been a long-standing problem, studied since the availability of upper air soundings, (e.g. Newton 1950). Simulations of squall lines with numerical models (e.g. Hane 1973; Moncrieff 1981; Thorpe et al. 1982; Rotunno et al. 1988; Weisman et al. 1988; Liu and Moncrieff 2001; Robe and Emanuel 2001; Weisman and Rotunno 2004) show that environmental wind shear is crucial to their organization. Rotunno et al. (1988) and Weisman et al. (1988), widely known as RKW and WKR, respectively, emphasized that the cold pool-shear interaction may greatly prolong the lifetimes of squall lines and enhance their intensities.

In an environment without shear, convective downdrafts bring low entropy air from the mid-troposphere down to near the surface, which then forms a surface-based cold pool, where it is detrimental to further convection. On the other hand, the cold pool can propagate horizontally as a density current, generating circulations which lift environmental boundary layer air to its level of free convection, and triggering new convective cells. When the environment is sheared, the circulation associated with the
shear may balance the circulation associated with the cold pool on the downshear side,
promoting deeper lifting. The case where the cold pool is roughly in balance with the
shear has been called the optimal state, meaning a state in which the system maintains an
upright updraft and repeatedly generates new cells on its leading edge (Xu et al. 1996;
Xue et al. 1997; Xue 2000; Robe and Emanuel 2001).

Despite its importance, the effect of vertical wind shear has not been included
explicitly in parameterization schemes for large-scale models. This may cause biases in
quantities that directly regulate energy balance, such as cloud fraction, optical depth, and
radiative fluxes. These quantities are related to convective organization, which is
modulated by shear (e.g., Liu and Moncrieff 2001).

The aim of this study is not to simulate squall lines or other specific mesoscale
storm types per se, but rather to investigate the influence of vertical shear on mean
precipitation and convective organization in the tropics in statistical equilibrium. We
investigate this in cloud-resolving simulations of a small tropical region in which the
interaction of that region with the surrounding environment is represented through a
simple parameterization of the large-scale circulation.

When the large-scale circulation is parameterized, the model itself can determine
the occurrence and intensity of deep convection. This is as opposed to more traditional
methods, in which otherwise similar numerical experiments are performed with specified
large-scale vertical motion, strongly constraining the bulk properties of convection a
priori (e.g., Mapes 2004). The large-scale parameterization here is the weak temperature
gradient (WTG) method (e.g., Sobel and Bretherton 2000; Raymond and Zeng 2005;
In this method, horizontal mean temperature anomalies in the free tropical troposphere, relative to a prescribed target profile, are strongly relaxed towards zero. This represents the effects of compensating vertical motion, communicated to large distances by gravity waves (e.g., Bretherton and Smolarkiewicz 1989) so as to maintain weak horizontal pressure and temperature gradients. The parameterized adiabatic cooling by the large-scale vertical velocity approximately balances the diabatic heating explicitly simulated by the cloud-system resolving model (CRM).

Parameterizations of large-scale dynamics have been used for a range of idealized calculations. Among these, Sessions et al. (2010) studied the response of precipitation to surface horizontal wind speed with fixed sea surface temperature (SST) using a 2-D CRM under WTG. They demonstrated the existence of multiple equilibria corresponding to precipitating and non-precipitating states for the same boundary conditions but different initial conditions, corroborating the findings of Sobel et al. (2007) in a single column model with parameterized convection. Wang and Sobel (2011) showed the equilibrated precipitation as a function of SST using both a 2-D and 3-D CRM. Both of these studies show monotonic increases in surface precipitation rate (in the precipitating state, where it exists) with either increasing surface wind speed at fixed SST or vice versa. Here we extend these studies to examine the response of convection to vertical shear of the horizontal wind.

This paper is organized as follows. We describe the model setup and experiment in section 2. In section 3 we show how convective organization, mean precipitation, and other thermodynamic and dynamic quantities vary with the magnitude of shear when the
depth of the shear layer is fixed and approximately equal to the depth of the troposphere. In section 4 we show the effect of variations in the depth of the shear layer. We conclude in section 5.

2. Experiment Design and Model Setup

2.1 Experiment design

The model used here is the Weather Research and Forecast (WRF) model version 3.3, in three spatial dimensions, with doubly periodic lateral boundary conditions. The experiments are conducted with Coriolis parameter $f = 0$. The domain size is $196 \times 196 \times 22$ km$^3$, the horizontal resolution is 2 km. 50 vertical levels are used, with 10 levels in the lowest 1 km. Vertically propagating gravity waves are absorbed in the top 5 km to prevent unphysical wave reflection off the top boundary by using the implicit damping vertical velocity scheme (Klemp et al. 2008). Microphysics scheme is the Purdue-Lin bulk scheme (Lin et al. 1983; Rutledge and Hobbs 1984; Chen and Sun 2002). This scheme has six species: water vapor, cloud water, cloud ice, rain, snow, and graupel. The 2-D Smagorinsky first order closure scheme is used to parameterize the horizontal transports by sub-grid eddies. The surface fluxes of moisture and heat are parameterized following Monin-Obukhov similarity theory. The Yonsei University (YSU) first order closure scheme is used to parameterize boundary layer turbulence and vertical subgrid scale eddy diffusion (Hong and Pan 1996; Noh et al. 2003; Hong et al. 2006). In this scheme nonlocal counter gradient transport (Troen and Mahrt 1986) is represented, and the local Richardson number, temperature, and wind speed determine the depth of the
boundary layer.

Radiative cooling is set to a constant rate of 1.5 K day$^{-1}$ in the troposphere. The stratospheric temperature is relaxed towards 200 K over 5 days, and the radiative cooling in between is matched smoothly depending on temperature as in Pauluis and Garner (2006):

$$Q_{rad.\ cooling} = \begin{cases} -1.5 \, K\cdot day^{-1} \, for \, T > 207.5K \\ \frac{200K-T}{5 \, day} \, elsewhere \end{cases}$$

The vertical wind shear is maintained by a term in the horizontal momentum equation which relaxes the horizontal mean zonal wind to a prescribed profile, $U(z)$, with a relaxation time scale of 1 hour. Figure 1a shows $U(z)$ for a constant shear layer depth of 12 km and varying shear magnitude, specified by varying the wind speed at the top of the shear layer from 10 m s$^{-1}$ to 40 m s$^{-1}$ in increments of 10 m s$^{-1}$ while maintaining $U=0$ m s$^{-1}$ at the surface. Hereafter we refer to these experiments as U0, U10, U20, U30 and U40. Figure 1b, shows profiles in which we vary the depth of the shear layer while fixing the wind speed at the top of the layer at 20 m s$^{-1}$. In all cases, we relax the horizontal mean meridional wind to zero.

Surface fluxes of sensible heat (SH) and latent heat (LH) are prescribed and held constant at each grid point and each time step. Three sets of values are used for the total
heat flux and its individual components: 160 W m\(^{-2}\) (low), partitioned as SH=15 W m\(^{-2}\),
LH=145 W m\(^{-2}\); 206 W m\(^{-2}\) (moderate), partitioned as SH=22 W m\(^{-2}\), LH=184 W m\(^{-2}\);
and 280 W m\(^{-2}\) (high), partitioned as SH=30 W m\(^{-2}\), LH=250 W m\(^{-2}\). These represent a
range of deviations from the vertically integrated radiative cooling, which is 145 W m\(^{-2}\).
We consider only positive deviations from the radiative cooling, as we are most
interested in equilibrium cases featuring significant convection. The parameterized
circulations in our model tend to result in positive gross moist stability, so that the mean
precipitation rate increases with the excess of surface fluxes over radiative cooling (e.g.,

We prescribe surface fluxes, rather than just SST (as in previous work) because
for different shear profiles, convective momentum transport induces significant changes
in surface wind speeds, even with a strong relaxation imposed on the surface winds. This
causes surface fluxes to vary significantly with shear if the fluxes are calculated
interactively. Varying fluxes by themselves will change the occurrence and properties of
deep convection, apart from any effects of shear on convective organization. We wish to
completely isolate the direct effect of shear, without considering this modulation of
surface fluxes. Also, prescribing surface fluxes will eliminate any feedback from cold
pools.

The model is run for 40 days for each simulation, and the output data is sampled
every 12 hours. After the first 5 days, the simulations reach approximate statistical
equilibrium (see Figure 3 below). The analysis is performed over this equilibrium period
only, neglecting the first 5 days.
2.2 WTG

We use the WTG method to parameterize the large scale circulation, as in Wang and Sobel (2011), whose methods in turn are closely related to those of Sobel and Bretherton (2000) and Raymond and Zeng (2005). Specifically, we add a term representing large-scale vertical advection of potential temperature to the thermodynamic equation. This term is taken to relax the horizontal mean potential temperature in the troposphere to a prescribed profile:

\[
\frac{\partial \theta}{\partial t} + \ldots = -\frac{\bar{\theta} - \theta_{RCE}}{\tau} \quad \ldots(2),
\]

Where \(\theta\) is potential temperature, \(\bar{\theta}\) is the mean potential temperature of the CRM domain (the overbar indicates the CRM horizontal domain average), \(\theta_{RCE}\) is the target potential temperature taken from a 6-month long radiative-convective equilibrium (RCE) run. Based on previous work in this configuration with this model, we are confident that the initial conditions do not influence the statistical properties of the results, except that we avoid any possible dry equilibrium state (Sobel et al. 2007; Sessions et al. 2010) by starting with a humid, raining state. \(\tau\) is the Newtonian relaxation time scale, taken to be 3 hours in our simulations. As \(\tau\) approaches zero (a limit one may not be able to reach due to numerical issues), this becomes a strict implementation of WTG and the horizontal mean free troposphere temperature must equal \(\theta_{RCE}\). In general, \(\tau\) is interpreted as the time scale over which gravity waves propagate out of the domain, thus reducing the
horizontal pressure and temperature gradients (Bretherton and Smolarkiewicz 1989).

Finite $\tau$ allows the temperature to vary in response to convective and radiative heating.

The large scale vertical circulation implied by this relaxation constraint is $W_{WTG}$, the WTG vertical velocity,

$$W_{WTG} \frac{\partial \theta}{\partial \eta}(-\frac{\bar{\rho}g/\mu}{\tau}) = \frac{\bar{\theta} - \theta_{REC}}{\tau} \quad \ldots (3),$$

Where $\rho$ is the density, $\eta$ is the mass based vertical coordinate of WRF, and $-\bar{\rho}g/\mu$ is part of the coordinate transformation from $z$ to $\eta$. $\eta$ is defined as $\eta = \frac{P_d - p_d^F}{\mu}$, where $P_d$ is the dry pressure, $p_d^F$ is a constant dry pressure at the model top, and $\mu$ is the dry column mass. Within the boundary layer, following Sobel and Bretherton (2000) we do not apply (3), but instead obtain $W_{WTG}$ by linear interpolation from surface to the PBL top. Unlike in previous studies with our implementation of WTG, the PBL top is not fixed, but is diagnosed in the boundary layer parameterization scheme (discussed below).

The scheme determines a PBL top at each grid point, and we use the maximum value in the computational domain at each time step as the PBL top for the computation of $W_{WTG}$.

Transport of moisture by the large-scale vertical motion introduces an effective source or sink of moisture to the column. The moisture equation is updated at each time step by adding the following terms associated with the WTG vertical velocity:

$$\frac{\partial q}{\partial t} + \ldots = -W_{WTG} \frac{\bar{\theta}q}{\partial \eta}(-\frac{\bar{\rho}g/\mu}{\tau}) \quad \ldots (4),$$

Where $q$ is the moisture mixing ratio. The right hand side of equation (4) is the advection by the large scale vertical velocity $W_{WTG}$. We assume that the moisture field is horizontally uniform on large scales, thus neglecting horizontal advection.
3. Response to a shear layer of fixed depth

a. Convective Organization and Precipitation

Figure 2 shows randomly chosen snapshots of hourly surface rain for different values of shear strength and surface fluxes. In the case of low surface fluxes (Figure 2a) convection in the unsheared flow is random in appearance and has a “popcorn” structure. For small shear (cases U10 and U20) convection starts to organize but does not maintain a particular pattern. In some snapshots it has lines normal to the shear direction, while in others it loses this structure and appears to form small clusters. For strong shear, lines of intense precipitation form parallel to the shear direction.

In the case of moderate surface fluxes (Figure 2b) the unsheared flow’s convection is random and distributed uniformly across the domain, but less so than in the case of low surface fluxes, as there are arcs and semi-circular patterns. Under weak shear (case U10) there are organized convective clusters in part of the domain. As the shear increases further, lines of intense precipitation (in brown shading) are trailed by lighter rain (blue shading) which propagate downshear (eastward). The organization in all cases is three-dimensional.

For high surface fluxes (Figure 2c), convection is organized in linear forms in the absence of vertical wind shear, loses linear structure with moderate shear (U10), and transform into “aggregated” states in which intense precipitation only occurs in a small part of the domain. Moncrieff and Liu (2006) simulated three-dimensional propagating
shear-perpendicular MCS in unidirectional quasi-constant vertical shear. Mesoscale
downdrafts/density currents were important, and synoptic waves played a part in the
intermittent occurrence of the MCS episodes. The small domain setup under WTG
approximation in this study and lack of synoptic-scale variability likely suppress
intermittency and may explain the lack of shear-perpendicular systems as prevalent
convective regime in our simulations.

Shear-parallel bands were observed in the eastern tropical Atlantic during GARP
Tropical Atlantic Experiment (GATE), and were reproduced in simulations of that
experiment by Dudhia and Moncrieff (1987). Although there are a number of differences
between those simulations and ours, there are a number of similarities between their
results and those found here, including downgradient convective momentum transport
discussed later in section c 3.

To further quantify the impact of the shear on precipitation, Figure 3 shows time
series of the domain mean daily rain rate for the different shear strengths. Statistical
equilibrium is reached in the first few days. The magnitude of the temporal variability is
minimized in the unsheared case, and increases with increasing surface fluxes, while it is
maximized in the cases U30 and U40 for low surface fluxes (Figure 3a), and in U20 for
higher surface fluxes (Figure 3b and 3c). In many of the simulations the variability is
quasi-periodic, with periods on the order of days. We are interested here primarily in the
time-averaged statistics and have not analyzed these oscillations in any detail.

To define a quantitative measure of convective organization, we first define a
blob as a contiguous region of reflectivity greater than 15 dbz in the vertical layer 0-2 km (Holder et al. 2008). Figure 4a shows a normalized probability density function (PDF) of the total (as the sum of all times for which we have data) number density of blobs, and Figure 4b shows the normalized PDF of the total area of blobs in the domain for the moderate surface fluxes case. The number of blobs decreases as convection clusters into aggregated structures with stronger shear. The areal coverage of convection increases with stronger shear as the tail of the PDF spreads towards larger areas. The other cases of surface fluxes are qualitatively similar and not shown.

c. Mean Precipitation, Thermodynamic Budget and Large-Scale Circulation

1) Mean Precipitation

A key question we wish to address is the dependence of the mean precipitation in statistical equilibrium as a function of the shear. Figure 5 shows the domain and time mean precipitation as a function of shear for three cases of surface fluxes, as a direct model output (in red) and as diagnosed from the energy budget (in blue) as we will discuss in section c.4. The most striking feature is that for low and moderate surface fluxes, the mean precipitation is a non-monotonic function of the shear (Figure 5a and 5b). For low surface fluxes, small shear brings the precipitation below that in the unsheared case, achieving its minimum at U20. For strong shear (U30 and U40), however, precipitation increases not only relative to the unsheared case but also above the surface fluxes, which indicates moisture import by the large-scale circulation. For moderate surface fluxes, the structure of the non-monotonicity differs from that in the low surface fluxes case. The minimum precipitation now shifts to U10, above which the
behavior is monotonic. Again, strong shear is required to bring precipitation above that in the unsheared case.

For high surface fluxes, the behavior is monotonic, and small shear suffices to bring precipitation above that in the unsheared case. The difference between the minimum and maximum precipitation in the high surface flux case exceeds that in the lower surface flux cases, which is also (as one would expect) manifested in parameterized large scale vertical velocity $W_{WTG}$ as we will show in Figures 8c and 8f. There is no obvious relationship, however, between mean precipitation and organization. While small shear can organize convection from a completely random state, the mean of that more organized convection need not be larger than that in the unsheared random state (Figures 2a and 2b).

To examine the role of the cold pool on the relationship between mean precipitation and shear, we have also performed a set of similar simulations but with cold pools suppressed by setting evaporation of precipitation to zero at levels below 1000 m. Although, as expected, mean precipitation increases in these simulations relative to those in which precipitation can evaporate at all altitudes, the dependence of mean precipitation on the shear remains the same (not shown). This suggests that the cold pools are unlikely to be a key factor controlling the mean precipitation-shear relationship.

2) Moist Static Energy (MSE) budgets

The moist static energy (MSE) budget can be a useful diagnostic for precipitating convection as MSE is approximately conserved in adiabatic processes. It is the sum of
thermal, potential and latent heat terms:

\[ h = c_p T + gz + L_v q \]  \( \cdots (5) \)

Where \( c_p \), \( L_v \), and \( q \) are the heat capacity of dry air at constant pressure, latent heat of condensation, and water vapor mixing ratio, respectively.

To define the basic state from which perturbations will be computed, the equilibrium vertical profiles of temperature, water vapor mixing ratio, and MSE for the unsheared case of moderate surface fluxes of 206 W m\(^{-2}\) are shown in Figure 6 (other unsheared cases for low and high surface fluxes are very similar). Due to the fixed radiative cooling, the tropopause is at \(~14\) km, and the melting level is at \(~4\) km.

Figure 7 shows the time and domain mean profiles of temperature, water vapor mixing ratio, and moist static energy, all expressed as perturbations from the same quantities in the unsheared experiment. There is a weak sensitivity to the shear in the temperature profile for low surface fluxes, becoming larger as surface fluxes increase. Recall that the temperature is continually being strongly relaxed back towards the target profile. The temperature perturbation is positive in the mid to upper troposphere and negative in the boundary layer in the strong shear case.

The moisture profile is more sensitive to the shear than temperature is, but varies little with increasing surface fluxes. Above the boundary layer the strong shear case is moister than the unsheared case by about 0.2 g kg\(^{-1}\) and drier in the boundary layer by about 0.5 g kg\(^{-1}\). The weak shear case is drier than the unsheared case at all levels for all three cases of surface fluxes. This increasing dryness with shear is also apparent in the
snapshots of surface rainfall (Fig. 2). The moist static energy variations with shear are dominated by the moisture term, are very similar for all three cases of surface fluxes, and depend non-monotonically on the shear. The non-monotonicity remains the same for all cases of surface fluxes, unlike the large-scale vertical velocity and mean precipitation.

3) Large-Scale Circulation

Figure 8 shows the vertical profiles of large-scale vertical velocity $W_{WTG}$ (a)-(c), and its maximum value with respect to the vertical (d)-(f) for the three cases of surface fluxes. For low surface flux, $W_{WTG}$ is very weak (less than 1 cm s$^{-1}$), and its absolute value varies little with shear. As the surface fluxes increase, $W_{WTG}$ increases, but the effect of the shear is much more significant in the highest surface fluxes case, where $W_{WTG}$ increases by 4 cm s$^{-1}$ from the unsheared case to the case with the strongest shear.

4) Normalized Gross Moist Stability

In order to diagnose the mean precipitation from the point of view of the moist static energy budget, we use the diagnostic equation for precipitation as in, e.g., Sobel (2007) or Wang and Sobel (2011); see also Raymond et al. 2009:

$$ P = \frac{1}{M} (E + H + \langle Q_R \rangle) - \langle Q_R \rangle - H $$

Where $\langle . \rangle = \int_{p_0}^{p_f} \rho dz$ is the mass weighted vertical integral from the bottom to the top of the domain. $P$, $E$, $H$, and $Q_R$ are precipitation, latent heat flux, sensible heat flux, and radiative cooling rate. We have also utilized the large-scale vertical velocity and the moist static energy introduced in the above two subsections to define
\[ M = \frac{< W_{wTG} \frac{\partial \tilde{h}}{\partial z} >}{< W_{wTG} \frac{\partial \tilde{s}}{\partial z} >} \] as the normalized gross moist stability, which represents
the export of moist static energy by the large-scale circulation per unit of dry static
energy export. Here \( s \) is the dry static energy (sum of the thermal and potential energy
only, without the latent heat term), and the overbar is the domain mean.

The above equation is not predictive because we use the model output to compute
the terms; in particular, we do not have a theory for \( M \). Nonetheless, it gives a
quantitative, if diagnostic, understanding of the role played by large-scale dynamics in
controlling precipitation. We must first verify that our moist static energy budget closes
well enough that the precipitation calculated from equation (6) agrees well with the
model output precipitation. This is the case, as shown in blue in Figure 5.

As shown in Figure 5, the variations of \( M \) with respect to shear (themselves
shown in Fig. 9) explain those in the mean precipitation. Since both surface fluxes and
radiative cooling are constant in each plot in Fig. 5, variations in \( M \) are the only factor
controlling the variations in precipitation computed by equation (6), which is quite close
to the actual simulated precipitation.

Maximum \( M \) means maximum export of moist static energy by the large-scale
circulation per unit of dry static energy export. Since radiative cooling and surface fluxes
are prescribed, the moist static energy export is also prescribed, and variations in \( M \) must
correspond to variations in dry static energy export. Since dry static energy export
changes can only be balanced by changes in the rate of condensation (radiative cooling,
again, being fixed) and, hence, in the precipitation rate. For the case of low surface
fluxes, $M$ exceeds 1 for the cases U10 and U20; this is because of the low level
subsidence and upper level ascent in the $W_{WTG}$ profile, with midlevel inflow bringing in
relatively low moist static energy air.

c. Convective Cloud Properties

1) Cloud Fraction

The vertical profile of cloud fraction for the three values of surface fluxes is
shown in Figure 10. The cloud is defined as the set of grid points where the mixing ratio
of cloud hydrometeors (water and ice) is greater than 0.005 g kg$^{-1}$. Generally, there are
three peaks: a shallow peak at 1 km, a midlevel peak related to detrainment at the melting
level at about 4 km, and a peak associated with deep convection at 9-12 km. When the
cloud fraction in the deep convective peak becomes large, we interpret it as stratiform
cloud.

In all three cases, the shear has almost no effect on the shallow convection. For
low surface fluxes (Figure 10a) the effect of strong shear is seen mainly in the midlevels,
where cloud fraction increases from 30% in the unsheared flow to 60%. A modest
stratiform layer forms as cloudiness increases from 10% to 30%.

For moderate surface fluxes (Figure 10b) the strong shear, while causing an
increase of more than 40% in the midlevel peak over the unsheared case, also leads to
100% cloud cover in the layer 9-12 km. It is also interesting to notice a transition from a
single peak in the high clouds at 9 km in the unsheared and weak shear cases to a cloudy
layer 5-12 km deep in the strong shear. In Figure 10c near-total deep cloudiness is
determined by the strong, persistent convection associated with the high surface fluxes. The shear has no effect on the cloud fraction at upper levels, since it is 100% even with no shear. The effect of shear on mid-level cloudiness is clear, however, as cloud fraction increases over 35% from the unsheared to the strongest shear flow. The cloud cover in the midlevel increases monotonically with shear, but the deep cloudiness does not (Figure 10a and 10b), behaving instead more like mean precipitation. We discuss this further in section 3.c.3.

2) Convective Mass Flux

Figure 11 shows the convective mass fluxes in both updrafts and downdrafts. Updrafts are defined here as including all grid points with liquid water and ice content greater than 0.005 g kg\(^{-1}\) and vertical velocity greater than 1 m s\(^{-1}\), normalized by the total number of grid points. The downdrafts are defined including all grid points with vertical velocity less than -1 m s\(^{-1}\). The updraft mass fluxes are about twice as large as the downdraft mass fluxes. Both have two peaks, in the lower and upper troposphere, both of which strengthen by about a factor of 3 from lowest to highest surface fluxes.

Despite different convective organization for different shear profiles, the vertical profiles of the updrafts and downdrafts have similar shapes. For the downdrafts, the lower tropospheric peak exceeds the upper tropospheric one for all three cases of surface fluxes, and are similar for different shear strengths. The largest difference occurs in the case of highest surface fluxes, in which the downdraft in the lower peak for the smallest shear is stronger than for the strongest shear by about 20%. The effect of the shear on the upper tropospheric peak, however, is more prominent. The strongest shear causes the
downdraft mass flux to strengthen by 50%.

The updraft mass fluxes in the low surface fluxes case are greater in the lower troposphere than in the upper troposphere, due to the dominant role of the shallow convection, while in the moderate surface fluxes case both peaks are almost comparable, and in the high surface fluxes case the upper peak is larger due to deep clouds. Although with high surface fluxes there is an increase of 25% in the upper tropospheric updraft from the weakest to strongest shear, the effect of the shear on the updraft is smaller than in the downdraft and has negligible impact on the lower tropospheric peak, and, unlike the downdraft, is non-monotonic, similarly to cloud fraction.

3) Momentum Fluxes

Another collective effect of the cloud population and its organization on the large-scale flow results from vertical fluxes of horizontal momentum, including both convective momentum transport and gravity wave momentum transport (Lane and Moncrieff 2010, Shaw and Lane 2013). We evaluate these momentum fluxes as a function of the shear strength. Figure 12 shows the vertical profiles of the time and domain mean zonal momentum fluxes $\rho u'w'$ where $u'$ and $w'$ are the zonal and vertical velocity perturbations from the horizontal average, respectively, and the overbar is the horizontal mean.

The magnitude of the net momentum flux is a monotonic function of the shear. It is negligible for all unsheared cases, as expected, and negative (directed down the gradient of the mean zonal wind) and peaks close to the top of the shear layer for the
sheared cases. This negative momentum flux would act (if it were not strongly opposed
by the imposed relaxation) to accelerate the mean horizontal wind in the lower
troposphere and decelerate it in the upper troposphere and the stratosphere. The
amplitude of the momentum transport also increases with surface fluxes. Interestingly,
for the highest surface fluxes the momentum flux in the U10 case (Figure 12c), is up
gradient in the lower troposphere and peaks at about 4 km, while it is down gradient in
the upper troposphere.

In the 2-D analytic steering-level model of Moncrieff (1981) the updrafts tilt
downshear and precipitation falls into the updrafts weakens the cold pool and causing
upgradient momentum transport. With the exception of the lower troposphere in the U10
case for the largest surface fluxes, our momentum fluxes are primarily downgradient
throughout the troposphere. This may be due to the fact that none of our simulations
show truly long-lived, quasi-2D shear-perpendicular squall lines as in Moncrieff’s model,
as discussed further below.

4. Response to Different Shear Depths
In this section we investigate the effect of varying the depth of the shear layer. We repeat
the above calculations but with shear depths of 1500 m, 3000 m, 4500 m, 6000 m, and
9000 m. In each case, the wind speed is held fixed at 20 m s\(^{-1}\) at the top of the layer
(Figure 1b). Surface latent and sensible heat fluxes are held fixed at the intermediate
values from the previous section, totaling 206 W m\(^{-2}\).

As of convective organization, Figure 13 shows snapshots of hourly surface
precipitation for a period of 7 consecutive hours, chosen from the last 7 hours of each
simulation. Each row corresponds to a different shear case: 1500, 3000, 4500, 6000, and
9000 m, from top to bottom. Most of these snapshots are a mixture of linear squall lines
and supercell-like 3D entities, which have strong rotational components and tend to split
into left and right movers (e.g., the 4500 m case in the 3rd row of Fig. 13). For shallow
shear of depth 1500 m, convection is to some extent organized in lines normal to the
shear (as seen in some of the snapshots) Nonetheless, the shear-perpendicular squall lines
prevalent in analytical models (e.g., Moncrieff 1992) and 2D numerical simulations (e.g.,
Liu and Moncrieff 2000) do not become fully established even in the shallow shear case.
Mid-level shear (3000-4500 m) is associated with quasi-linear structure parallel to the
shear with intense precipitating cores trailed by lighter precipitation. As the shear depth
increases above that – approaching the deep shear cases analyzed in the preceding
sections - the quasi-linear regime is still less prominent. For deeper shear of 9000 m,
convection aggregates in clusters

Figure 14 shows time and domain mean precipitation as a function of the shear
depth. The shallowest shear layer, with depth 1500 m, produces the least precipitation,
about 30% less than the unsheared case, despite a greater degree of convective
organization compared to the unsheared flow (not shown). Doubling the shear layer depth
almost doubles the precipitation. The mid-depth shear layers, with tops at 3000 - 4500 m
produce the greatest precipitation; in this sense, these intermediate shear layer depths are
“optimal”. Although the convection is in statistical equilibrium, this is in agreement with
studies of transient storms of Weisman and Rotunno (2004). While it was not the case
that the optimal state produces the greatest surface precipitation in their original papers
and later work, Bryan et al. (2006) demonstrated that optimal state is indeed associated
with the greatest precipitation in several mesoscale models. Bryan et al. (2006) further
attributed this discrepancy to numerical artifacts in the model used by Weisman and
Rotunno (2004). Increasing the shear depth above 4500 m reduces the precipitation
again, with the values for 6000 m and 9000 m depths being smaller than those for the
intermediate depths.

We have performed simulations analogous to those in Fig. 14 but with low and high
surface fluxes (not shown). In these simulations, we find a similar dependence of the
mean precipitation on the shear depths. The relationship shown in Fig. 14 between mean
precipitation and shear depths appears to be qualitatively independent of the magnitude of
the mean precipitation, at least in the regime studied here.

The vertical profiles of the large-scale vertical velocity as a function of the shear
layer depth are shown in Figure 15. As we expect, the amplitude differences are largely
consistent with those in the mean precipitation. The peak value, for instance, is smallest
for the shallow shear case, and largest for the mid-level shear. The cases of 3000 m and
4500 m are almost identical, while there is a small increase in precipitation for 4500 m
over that at 3000 m. This is due to the more abundant moisture in the lower to mid
 troposphere for the case of 4500 m, as shown in Figure 16. Dominated by moisture, moist
static energy has a maximum for the 4500 m case.

Figure 17 shows the mass fluxes in updrafts and downdrafts for the different shear
depths. Although the maximum mean precipitation occurs for the shear depth of 4500 m,
the maximum updraft mass flux occurs at 3000 m shear depth. This demonstrates that
convective mass flux need not vary in the same way as the precipitation rate. The
response of the downdrafts is much weaker than that of the updrafts. In fact, the
downdraft mass flux for the shallow shear is almost identical to that for the deeper shear
layers with depths 6000 m and 9000 m.

Finally, Figure 18 shows the domain averaged time mean zonal momentum fluxes
$\rho u'w'$ for different shear depths. Similar to the analytic model of Moncrieff (1992),
momentum flux here is down the mean gradient for all shear depths, as in Fig. 12, and
achieves the minimum at the top of the shear layer in each profile. This is likely due to
momentum mixing, consistent with shear-parallel lines (Dudhia and Moncrieff 1987).
The downward momentum transport is greatest when the shear is shallow: 1500 m and
3000 m deep, and becomes smaller for deep shear (9000 m); similar to the cases with
uniform shear depth (Fig. 12). This momentum flux dependence on the shear depth
differs from the variations in the mean precipitation. As with other measures of
organization, momentum flux apparently does not have a direct relationship to
precipitation in our simulations.

5. Summary and Discussion

We have quantified the effect of vertical wind shear on atmospheric convection in
a series of 3-D CRM simulations with large-scale dynamics parameterized according to
the weak temperature gradient approximation. We varied the shear while holding surface
heat fluxes fixed. We repeated the calculations for three different values of surface
As surface fluxes are increased, the strength of the simulated convection increases, as measured by domain-averaged precipitation. Precipitation increases more rapidly than the surface latent heat flux, because of parameterized large-scale moisture convergence. The three cases thus correspond to weak, moderate and strong convection.

The response of mean precipitation to shear in statistical equilibrium for the lower two surface flux cases is non-monotonic in the magnitude of the shear, with a minimum precipitation at an intermediate shear value. The shear value at which the minimum precipitation occurs is somewhat different for low and moderate surface fluxes. Only for strong shear does the precipitation exceed that in the unsheared flow. In the case of the highest surface fluxes used, the response to shear is monotonic and a small amount of shear is enough to cause the precipitation to exceed that of the unsheared flow.

The dependences of large-scale vertical velocity and the moist static energy on shear are both similar to the dependence of precipitation on shear. The dependence on shear of the normalized gross moist stability, which combines these two quantities in a way relevant to the column-integrated moist static energy budget, is found to explain the variations in mean precipitation with shear well.

Despite the relative smallness of the changes in the mean precipitation with shear, shear has a strong effect on convective organization. Weak shear is sufficient to organize convection even under weak surface fluxes when the large-scale vertical motion is negligible. Stronger shear can organize convection into convective clusters and squall line-like structures with lines of intense precipitation trailed by lighter rain. As the surface fluxes and domain-averaged precipitation increase, however, convection is found
to be organized even in the absence of vertical wind shear.

The wind shear also has a significant effect on cloud cover, which increases with the shear (especially high clouds); convective mass flux (in particular the downdraft mass flux); and momentum fluxes, as more momentum is transported downward when the shear increases.

When the total change in velocity over the shear layer is fixed but the layer depth is varied, mid-level shear depths are found to be optimal for producing maximum mean precipitation, maximum large-scale vertical velocity and maximum column moist static energy. Convective organization, for this shear depth, is very similar to that for deeper shear layers, but with more intense lines of precipitation. Confining the shear in a shallow layer dries out the atmospheric column, leaving precipitation at a minimum.

We have neglected the complications of cloud-radiation feedback by fixing the radiative cooling rate in a simple relaxation scheme. In reality, longwave radiative cooling can be suppressed by the abundant upper tropospheric ice cloud in the deep tropics, which by itself is controlled by the shear. This effect will be investigated in a separate, future study.
Acknowledgement

This work was supported by NSF grant AGS-1008847. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation. We thank Dr. Mitchel Moncrieff and two anonymous reviewers for their insightful comments.
References


Klemp, J. B., J. Dudhia, and A. Hassiotis (2008), An upper gravity wave absorbing layer for NWP applications, Mon. Weather Rev., 136, 3987–4004,


List of Figures

FIG. 1. Wind profiles used in the simulations. (a) fixed depth of 12 km, (b) varying depths.

FIG. 2. Snapshots of hourly surface precipitation (mm hour\(^{-1}\)) for a period of 7 consecutive hours (each column), picked from the last 7 hours of the simulations. Each row corresponds to a different shear case. From top to bottom: U0, U10, U20, U30, and U40. (a) for low (b) moderate, and (c) high surface fluxes.

FIG. 3. Time series of daily precipitation. (a) low, (b) moderate, and (c) high surface fluxes. Colors indicate the value of the shear (m s\(^{-1}\)).

FIG. 4. Normalized probability density functions (PDFs) of (a) the total number density of blobs (number every 4x10\(^4\) km\(^2\)), and (b) the size of blobs in the domain (km\(^2\)).

FIG. 5. Time and domain mean model output precipitation (red), derived precipitation (blue), and surface fluxes (black) as a function of the shear. (a) low, (b) moderate, and (c) high surface fluxes.

FIG. 6. Vertical profiles of (from top to bottom): temperature, water vapor mixing ratio, and the moist static energy (MSE) for the unsheared case of moderate surface fluxes.

FIG. 7. Temperature, water vapor mixing ratio, and moist static energy, all expressed as differences from the unsheared case. (a) low, (b) moderate, and (c) high surface fluxes.

FIG. 8. (a)-(c) vertical profile of the large-scale vertical velocity \(W_{WTG}\). (d)-(f) \(W_{WTG}\) Maximum. (a) and (d) low, (b) and (e) moderate, and (c) and (f) high surface fluxes.
FIG. 9. Normalized gross moist stability $M$ as a function of the shear. (a) low, (b) moderate, and (c) high surface fluxes.

FIG. 10. Cloud fraction. (a) low, (b) moderate, and (c) high surface fluxes.

FIG. 11. Convective mass flux of updraft and downdraft. (a) low, (b) moderate, (c) high surface fluxes.

FIG. 12. Momentum fluxes. (a) low, (b) moderate, and (c) high surface fluxes.

FIG. 13. As Figure 2 but for different shear depths. From top to bottom: 1500, 3000, 4500, 6000, and 9000 m.

FIG. 14. Time and domain mean model output precipitation (red), derived precipitation (blue), and surface fluxes (black) as a function of the shear layer depth.

FIG. 15. Vertical profile of the large-scale vertical velocity $W_{WTG}$ for different shear depths.

FIG. 16. Temperature, water vapor mixing ratio, and moist static energy, all expressed as differences from the unsheared case, for different shear layer depths.

FIG. 17. Convective mass flux of updraft and downdraft for different shear depths.

FIG. 18. Momentum fluxes for different shear depths.
FIG. 1. Wind profiles used in the simulations. (a) fixed depth of 12 Km, (b) varying depths.
FIG. 2. Snapshots of hourly surface precipitation (mm hour$^{-1}$) for a period of 7 consecutive hours (each column), picked from the last 7 hours of the simulations. Each row corresponds to a different shear case. From top to bottom: U0, U10, U20, U30, and U40. (a) for low (b) moderate, and (c) high surface fluxes.
FIG. 3. Time series of daily precipitation. (a) low, (b) moderate, and (c) high surface fluxes. Colors indicate the value of the shear (m s⁻¹).
FIG. 4. Normalized probability density functions (PDFs) of (a) the total number density of blobs (number every $4 \times 10^4 \text{ km}^2$), and (b) the size of blobs in the domain ($\text{km}^2$).
FIG. 5. Time and domain mean model output precipitation (red), derived precipitation
(blue), and surface fluxes (black) as a function of the shear. (a) low, (b) moderate, and (c) high surface fluxes.
FIG. 6. Vertical profiles of (from top to bottom): temperature, water vapor mixing ratio,
and moist static energy (MSE) for the unsheared case of moderate surface fluxes.
FIG. 7. Temperature, water vapor mixing ratio, and moist static energy, all expressed as differences from the unsheared case. Top row, low, middle row, moderate, and bottom row: high surface fluxes.
FIG. 8. (a)-(c) vertical profile of the large-scale vertical velocity $W_{\text{WTG}}$. (d)-(f) $W_{\text{WTG}}$ Maximum. (a) and (d) low, (b) and (e) moderate, and (c) and (f) high surface fluxes.
FIG. 9. Normalized gross moist stability $M$ as a function of the shear. (a) low, (b)
moderate, and (c) high surface fluxes.
FIG. 10. Cloud fraction. (a) low, (b) moderate, and (c) high surface fluxes.
FIG. 11. Convective mass flux of updrafts and downdrafts. (a) low, (b) moderate, (c) high
surface fluxes.
FIG. 12. Momentum fluxes. (a) low, (b) moderate, and (c) high surface fluxes.
FIG. 13. As Figure 2 but for different shear depths. From top to bottom: 1500, 3000, 4500, 6000, and 9000 m.
FIG. 14. Time and domain mean model output precipitation (red), derived precipitation (blue), and surface fluxes (black) as a function of the shear layer depth.
FIG. 15. Vertical profile of the large-scale vertical velocity $W_{WTG}$ for different shear depths.
FIG. 16. Temperature, water vapor mixing ratio, and moist static energy, all expressed as
differences from the unsheared case, for different shear layer depths.
FIG. 17. Convective mass fluxes of updrafts and downdrafts for different shear layer depths.
FIG. 18. Momentum fluxes for different shear layer depths.