and high thermal conductivity of the Playa site lead to weak temperature gradients that affect the relative strength of terms in the heat flux tendency equation. A critical ratio of the gradient production to buoyant production of sensible heat flux is suggested to predict the CG behaviour.

Keywords Counter-gradient heat flux · Heat flux evolution · Similarity theory · Surface layer · Temperature evolution

1 Introduction

Parameterization of

Flux-gradient relationships within the atmospheric surface layer (ASL) are integral to climate modeling and numerical weather prediction. Most often flux estimates are made within the Monin-Obukhov Similarity Theory (MOST) framework (Beljaars and Holtslag, 1991). Under daytime, moderately unstable conditions, MOST has been shown to accurately estimate fluxes within the ASL (e.g. Dyer and Hicks, 1970; Businger et al., 1971; Högström, 1996; Foken, 2006). For nighttime conditions, the application of MOST is more nuanced. Effects due to increased advection, weak and possibly intermittent turbulence, drainage flows, low-level jets (Sun et al., 2012) and strong stratification complicate its application. Nonetheless, researchers have shown many instances where the application of MOST is still valid for moderately stable conditions (e.g. Monin and Yaglom, 1971; Nieuwstadt, 1984; Mahrt et al., 1998; Mahrt, 1999; Cheng et al., 2005). Difficulties arise when MOST is considered during the transition between convective daytime conditions and stratified nocturnal conditions. Adopting the terminology of Nadeau et al. (2011) this transition is broken into two portions. The afternoon transition begins when the surface sensible heat flux begins to decrease from its midday maximum followed by the evening transition when the surface sensible heat flux becomes negative, near sunset. In the present study, we use data collected during the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program to examine the evolution of near-surface heat-flux and temperature-gradients through the late afternoon and early evening transition (LAEET). In particular, we are interested in those cases where the near-surface heat flux ~~flows~~ counter to the local temperature gradient.

← just one citation? for LLJ?

is directed ....

Under typical daytime conditions, a well-mixed convective layer exists above an unstable surface layer. Within the surface layer, fluxes are considered to be constant with height and shear production of turbulence is important. Eddies generated from surface heating pass through the surface layer and impart energy into the mixed layer from below. Additionally, ~~entrainment fluxes mix down~~ warm, dry air is entrained from the free atmosphere, feeding energy and mass into the mixed layer throughout the day (Fedorovich et al., 2001; Pino et al., 2003; Angevine, 2007). Under nocturnal conditions, a stable boundary layer, characterized by weak and possibly intermittent turbulence and strong stratification, develops near the surface. The mixed layer becomes ~~cut off~~ decoupled from the surface and erodes into a residual layer, characterized by neutral stratification and weak turbulence (Stull, 1988; Mahrt et al., 1998; Mahrt, 1999). While the structure of the daytime and nocturnal boundary layers are fairly well understood, relatively little is known about the transition from daytime to nocturnal conditions.

better word?

Many researchers have noted that a greater understanding of the LAEET is important for ~~applications such as~~ model development, and better forcasts for wind energy production, convective storm initiation and pollutant dispersion (Cole and Fernando, 1998; Sorbjan, 1997; Acevedo and Fitzjarrald, 2003; Edwards et al., 2006; Angevine, 2007; Nadeau et al., 2011; Lothon and Lenschow, 2011; Lothon et al., 2014).

During the LAEET, the flow is inherently unsteady. Turbulence is non-stationary and anisotropic, fluxes are small and ~~the physics~~ and driving processes evolve on .. evolve on short time scales. Furthermore, during this transition period, the traditional concept of a surface layer and mixed layer does not exist (Grant, 1997). A variety of weak forcings drive the physics, turbulent mixing decreases and horizontal heterogeneity and differential cooling become increasingly important. Also, the traditional daytime scaling laws for the convective boundary layer (Deardorff, 1970) and surface layer (Monin and Obukhov, 1954) are no longer well-defined. Finally, after the surface sensible heat flux has reversed, entrainment ~~fluxes~~ continues to feed energy into the boundary layer for some time (Nieuwstadt and Brost, 1986; Sorbjan, 1997; Grimsdell and Angevine, 2002; Pino et al., 2006). These factors combined with a relative lack of observations make a thorough analysis of the LAEET difficult.

Until recently, the LAEET was rarely studied. Starting with the work of Nieuwstadt and Brost (1986), a number of LES studies have been conducted to understand the decay of the convective boundary layer. Over the years, the studies have increased in complexity and allowed for more realistic forcing time scales and boundary conditions (Sorbjan, 1997; Acevedo and Fitzjarrald, 2001; Brown et al., 2002; Edwards et al., 2006; Kumar et al., 2006; Pino et al., 2006; Goulart et al., 2010; Kumar et al., 2010; Rizza et al., 2013; Taylor et al., 2014). Additionally, a number of laboratory experiments have been conducted to study transitional stability (Comte-Bellot and Corrsin, 1971; Cole and Fernando, 1998; Kang et al., 2003). To a lesser extent, ~~field data is~~ observations are beginning to be used to study the decay of convective turbulence. Nadeau et al. (2011) used field data to successfully model the decay of turbulent kinetic energy in a convective surface layer over contrasting surface types. Later, the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) campaign was specifically designed to ~~observe~~ experimentally study the LAEET (Lothon et al., 2014). Perhaps the only field study to specifically study near-surface, flux-gradient relationships during the LAEET is the BLLAST study conducted by Blay-Carreras et al. (2014). Their work found a persistent time lag between the ~~moment~~ time of the buoyancy flux reversal and local gradient reversal. Typical lag times persisted between 30 and 80 minutes. They concluded that the phenomena might be site-dependent and that further studies were necessary. In light of this and the fact that nearly all numerical weather models assume that surface fluxes ~~flow~~ are directed down-gradient (Mahrt, 1999), this topic merits further study.

Here, we build upon the work of Blay-Carreras et al. (2014) by contrasting two experimental sites that strongly differ from the one used in their study. First, the Playa site is located on a large alkaline playa with no vegetation, shallow water table and high soil moisture. Second, the Sagebrush site is located over desert steppe with limited soil moisture. We use turbulence data collected in the ASL to study the evolution of near-surface heat-flux and temperature-gradient profiles through the LAEET. The goal of this study is to provide additional clarity regarding the evolution of near-surface heat flux and temperature gradients through the LAEET.