# A comprehensive investigation on afternoon transition of the atmospheric boundary layer over a tropical rural site

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## Abstract

The transitory nature of the atmospheric boundary layer few hours before and after the time of sunset has been studied comprehensively over a tropical station, Gadanki (13.45°N, 79.18°E), using a suite of in situ and remote sensing devices. This study addresses the following fundamental and important issues related to the afternoon transition (AT): Which state variable first identifies it the AT? Which variable best identifies ~~it~~ the AT? Does the start time of the AT ~~varies~~ vary with season and height? If so, which physical mechanism is responsible for the observed height variation in the start time of transition?

At the surface, the transition is first seen in temperature ($T$) and wind variance ($\sigma^2_{WS}$), ~100 min prior to the time of local sunset, then in vertical temperature gradient and finally in water vapour mixing ratio variations. Aloft, both signal-to-noise ratio (SNR) and spectral width ($\sigma$) show the AT nearly at the same time. The $T$ at the surface and SNR aloft are found to be the best indicators of transition. Their distributions for start time of AT with reference to time of sunset are narrow and consistent in both total and seasonal plots. The start time of transition shows some seasonal variation with delayed transitions occurring mostly in the rainy and humid season of northeast monsoon. ok Interestingly, in contrast to the general perception, the signature of the transition is first seen in the profiler data, then in the sodar data and finally in the surface data. This suggest~~ing~~s that the transition follows a top-to-bottom evolution. It indicates that other ~~forcings,~~ processes like entrainment, could also play a role in altering the structure of ABL during the AT, when the sensible heat flux decreases progressively. These ~~forcing terms~~ ~~process~~ mechanisms are quantified using a unique high-resolution dataset to understand their variation in light of the intriguing height dependency of the start time of AT.

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## 1 Introduction

The behaviour of atmospheric boundary layer (ABL) during the transition from a well-mixed layer during the day to a stably stratified layer during the night is quite complex and is also poorly understood. In recent years, the afternoon transition (AT) and evening transition (ET) of the ABL have gained ~~lot of~~ attention for various reasons (Lothon et al., 2014). These transitional regimes are found to be important for the vertical transport of species, like pollutants, water vapour and ozone (Klein et al., 2014), the inception and strength of the nocturnal low level jet (LLJ) (Mahrt, 1981; Van De Wiel et al., 2010), and the whole structure of the nocturnal boundary layer. Further, identification of the ABL becomes uncertain and there is no consensus on which scaling laws (day-time convective scaling due to surface buoyancy flux? or nocturnal boundary layer scaling due to surface wind stress?) would work well during this period (Pino et al., 2006). Further, the start time of transition and its duration could be different at the surface and aloft, because the turbulence may not immediately dissipate after the sunset (Busse and Knupp, 2012).

Researchers defined the transition in a variety of ways employing various parameters obtained from different instruments. Some of them treated the transition as an instantaneous process, while the others considered it as a process of few hours. The most popular and widely used definition is the reversal of surface heat flux (positive to negative) (Grant, 1997; Acevedo and Fitzjarrald, 2001; Beare et al., 2006; Angevine, 2008). A similar technique is employed by Nieuwstadt and Brost (1986), in which the AT is assumed to occur following the cessation of upward surface sensible heat flux. Edwards et al. (2006) noted that the shortwave heating starts to decrease much before the surface heat flux changes its sign. They included the shortwave heating in the definition of AT, which shifted the start of afternoon transition to an earlier time. Acevedo and Fitzjarrald (2001) identified the start time of the transition from a sharp decrease in the spatial temperature difference and end from the maximum spatial standard deviation of temperature. As seen above, all these definitions are based on surface measurements and do not account the physical processes occurring aloft during the transition.

The studies that used remote sensing measurements like wind profiling radars, sodars and lidars focused more on the processes aloft (mostly in the lower part of ABL) to define the AT. In a seminal study, Mahrt (1981) used a kinematic definition for AT period. According to Mahrt (1981) the AT is a 4-5 h time period, starts from the time of low-level wind deceleration (typically 2 h before the sunset) and ends when the flow at all levels turned towards the high pressure. Grimsdell and Angevine (2002) and Angevine (2008), using radar wind profiler measurements, noticed that both reflectivity (range-corrected signal-to-noise-ratio (SNR)) and the spectral width ($\sigma$) (a measure of turbulence) decrease sharply during the AT. The applicability of these approaches is always an issue, particularly when the turbulence is either weak or strong throughout the day or when the turbulence increases due to some other processes associated with katabatic winds or land see-breeze circulations (Sastre et al., 2012). Instead of defining the start and end times for AT, Busse and Knupp (2012) studied the variations in meteorological parameters with reference to the sunset time. They noted an increase in wind speed and a decrease in sodar return power in the lower ABL. They found that the AT has a relatively consistent pattern regardless of season.

A few studies employed models to understand or validate the occurrence of different types of transition (Brazel et al., 2005; Edwards et al., 2006; Pino et al., 2006; Sorbjan, 2007; Nadeau et al., 2011; Sastre et al., 2012). Brazel et al. (2005) studied the evening transition under weak synoptic forcing that favours the local thermal circulations and compared the observed transitions with models. Recently, Sastre et al. (2012) identified 3 types of evening transitions and evaluated performance of the Weather Research and Forecasting Advanced Research (WRF-ARW) model in reproducing these transitions by varying PBL parameterization schemes. They noted that all parameterizations reproduced the observed behaviour of AT in certain circumstances. Noting the need to understand the transitions in a better way, several field campaigns were conducted in recent years, employing both in situ and remote sensors, exclusively for better characterisation and modelling of the transitions. For instance, Cooperative Atmosphere-Surface Exchange Study (CASES-99) (Poulos et al., 2002), Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) (http://bllast.sedoo.fr/)(Lothon et al., 2014) and Phoenix Evening Transition Flow Experiment (TRANSFLEX) (Fernando et al., 2013). Recently, manned and unmanned aerial vehicles were used to study the vertical structure of lowest part of ABL during the AT (Bonin et al., 2013; Lothon et al., 2014).

Most of the above studies focussed on the variations in state variables like temperature, humidity, wind and turbulence, in the surface layer as they are easily accessible. Other studies characterized the evening transitions aloft, but neglecting the variations at the surface. Only a few studies that were based on campaign data and/or a few months of data dealt the transitions in totality, i.e., studied the variations at the surface and aloft (Busse and Knupp, 2012; Fernando et al., 2013; Lothon et al., 2014). Again, the data employed in those studies were limited, few days to 2 months. Certainly there is a need to characterize and understand the transitions at the surface and aloft in different seasons through systematic observations on a long-term basis. Further, earlier studies used different state variables to define the transition. Only a few studies focused on how these state variables vary with reference to the time of sunset (Busse and Knupp, 2012). Although some tower-based observations exist in the literature, the complete understanding of the transition over a deeper layer is certainly far from complete. This forms the basis for the

1 present study. In particular, the study tries to answer the following questions: How do the surface state variables and radar/sodar attributes vary during the transition and with reference to the time of sunset? Which state variable better identifies the transition? 1 How does the start time of transition varies with height and season? Which physical processes are responsible for the vertical evolution of the transition?

The paper is organized as follows: Sect. 2. introduces the measurement site, data and instrumentation employed. The variation of different state variables at the surface and aloft is studied with the help of a typical case study in Sect. 3. The start time of AT as identified by different state variables and their mean characteristics at the surface and aloft are studied with reference to the time of sunset. The questions posed above are discussed in light of present observations in Sect. 4. The important forcing terms on the ABL are estimated using a unique dataset to understand the role of entrainment in the afternoon transition. The important results are concluded in Sect. 5.

## 2 Data and site description

The present study follows an integrated approach, wherein several instruments available at National Atmospheric Research Laboratory (NARL), Gadanki (13.45° N, 79.18° E), India are extensively used. This site is located ~375 m above the mean sea level in a rural area in southeast peninsular India and is surrounded by hillocks (300-800 m within 10 km region) distributed in a complex fashion. The rainfall in this region is influenced primarily by two monsoons, southwest (June-September) and northeast (October-December) (Rao et al., 2009). Summer and winter are the other two seasons, covering the months of March-May and January-February, respectively.