An Observational Study of the Connection between Boundary Layer Structure and Precipitation in the U.S. Great Plains

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Abstract

This study is motivated by the disagreement between the MERRA model simulations and TRMM's observational precipitation in the Great Plains region of the United States. In order to diagnose this problem, the boundary layer and Lifting Condensation Level (LCL) relationship were examined further to understand what is happening, thermodynamically, through a precipitation event in the daytime and nighttime hours. A number of different datasets were used, including TRMM, CEOP, and NOAA Operational Data Stream datasets. Through careful observations in the summer months of 2003 and 2004, the boundary layer and LCL relationship showed that daytime precipitation events occurred when the boundary layer is lifted above the LCL, allowing the warm, moist air in the mixed layer to be elevated to the LCL. The nighttime precipitation events, however, were not characterized by this relationship. Through further research, the variables that cause nighttime precipitation, specifically in the Great Plains region, can be found.

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Introduction

The Global Modeling and Assimilation Office (GMAO) at Goddard Space Flight Center serves as an important asset to developing and using satellite observations, and constructing meteorological models to use in conjunction with that data. One current issue with these models is centered on the central Great Plains region. The models simulate summertime precipitation will occur at the peak high temperature portions of the day, but surface observations differ from these predictions. Surface observations show that precipitation occurs later, from early evening and into the early morning. The specific purpose of this project is to obtain a substantial amount of surface observation data for the purpose of understanding the relationship between the boundary layer structure and the timing of the precipitation, with the eventual goal of comparing that data with that of the models to diagnose the problem.

The boundary layer over this section of the United States will be studied extensively with surface and atmospheric profile observations to understand why the precipitation occurs closer to evening and nighttime hours, rather than mid-afternoon during the higher temperature points in the day. A vertical profile of the boundary layer can be made by looking at factors such as vertical winds and temperature profiles. These factors can aid in understanding turbulence kinetic energy in the boundary layer and other factors that contribute to lifting in the boundary layer. The turbulence kinetic energy inside of the boundary layer affects how well the layer itself is mixed as it carries moisture and temperature from the surface throughout the layer.

In addition to observations of the structure of the boundary layer, surface observations must also be looked at to eventually compare to the models. The surface observations will display different variables, like temperature and specific humidity, which occurred throughout the day at question. While displaying these observations alongside the precipitation events, the atmospheric variables can be compared to show how they work during precipitation and clear days.

Other factors apart from locally observed data will are relevant, but will not be discussed in any detail here. The Great Plains nocturnal jet over the Gulf of Mexico has an impact on the weather in the Great Plains region. This jet brings in moisture and advects warm ocean air over the region during the evening hours. The Low-Level Jet (LLJ) could be an explanation to the nighttime occurrence of precipitation in this region specifically. The NARR (North American Regional Reanalysis) models show that the peak of nighttime precipitation occurs at a maximum southerly flow associated with the nocturnal Great Plains low-level jets (Lee et al., 2006). The LLJ supplies the moist air to generate precipitation during nighttime hours. This aspect of nighttime precipitation should be continued with further research. Another possible factor that could affect this is the passage of mesoscale disturbances that propagate from the west, over the Rocky Mountains, and to the east during summertime. Observations indicate that convective initiations during the late afternoon over the Rocky Mountains self-organizes into mesoscale convective complexes, and those complexes tend to be sustained for a

considerable amount of time (Pritchard and Somerville, 2008). These disturbances can event dominate the diurnal cycle over the central United States.

The mission of this research project is to gain more information about the sometimes unpredictable behavior of the boundary layer in the Great Plains, its connection to the timing of the precipitation during the day, and apply that knowledge to improving the quality of the model output.

Analysis

Summertime convection generally originates in the lowest portion of the atmosphere inside the boundary layer, where turbulent mixing tends to be the greatest. For this reason, the boundary layer is being studied for this mission. Several factors provide an aid to convection that are observed for this project:

1) *Temperature and Specific Humidity*
   The temperature tends to be warmest at the surface, aiding to significant rising if it is more buoyant than the surrounding air. Vertical temperature profiles can be made to show the change in the variable with height. The temperature can also be used to help find the Lifting Condensation Level (LCL): with lower surface temperatures, the LCL tends to be lower. This is because the cooler air can hold less water vapor (specific humidity), and therefore complete saturation occurs at a lower height. The specific humidity of the air therefore plays a large role in the height of the LCL. If the specific humidity is higher, meaning that there is more water vapor in an air parcel, the LCL drops significantly to a lower pressure level to saturation. With higher surface temperatures, the LCL becomes higher as the specific humidity drops, and an air parcel has a longer track to get up to complete saturation, which is at the cloud base.
2) *Turbulence, Winds, and Buoyancy*
   One of the driving forces of the boundary layer height is the turbulence kinetic energy that fuels the mixing of the surface layer underneath the boundary layer. Large eddies inside of the boundary layer act as a transporter of air parcels: the turbulent motions move parcels towards the LCL and the parcel can condense.
3) *Latent heat*
   Once an air parcel is able to climb to the LCL to condense, the latent heat energy is the energy that pushes the condensed parcel (now a cloud) further up in height. “The latent heat stored in water vapor accounts for 80% of the fuel that drives atmospheric motions”, (Stull, 22). The amount of this latent heat determines how much lifting is occurring above the LCL, which further leads to whether or not convection will continue.

Data Sources

1) *Conventional Data*
   The Conventional data include all data that are not found by remote sensing satellites. These include, but are not limited to, wind profilers, rawinsonde, and dropsonde data. Before the Conventional data could be sorted and used, data went through quality control by the National Centers for Environmental Predictions to

remove any unnecessary data. The files made for this project were generated in the GMAO during the MERRA (Modern Era Retrospective-Analysis for Research and Applications) integration by reading this PREPBUFR data from the National Centers for Environmental Predictions and eliminating data their quality control flags said to reject. Thereafter, the data were written by GMAO into the format used for this project.

The PREPBUFR webpage with the station flag codes were found through NOAA (http://www.emc.ncep.noaa.gov/mmb/data_processing/prepbufr.doc/table_2.htm) gives the codes for aircraft measurements, rawinsondes, profilers, and dropsondes. Once the codes are known for each of the measurement tools, they can be used to find sites with wind profiler and radiosonde data.

The specific codes used for this research project were as follows: code 223 for wind profiler data, code 233 for aircraft dropsondes, and code 120 for rawinsonde data that measures temperature and specific humidity.

A control script was written to generate GrADS station observations for this conventional data from binary files, and sorted monthly for June, July, and August of 2003 and 2004. Once sorted, these files were viewed in GRaDS to see what data types are associated with a station. The data types were read using the PREPBUFR station observational flags. The latitude and longitude can be fixed to a specific region in the viewing area in GRaDS. Using this feature, several stations in the Great Plains region (30 N to 50 N, 97 W to 86 W) were viewed.

Four stations in particular were viewed: station 72248 in Louisiana at 32.47 N, 93.82 W with nearby profiler data, station 74560 in Illinois at 40.15 N, 89.33 W with CEOP station in Bondville and nearby profiler data, station 72649 in Minnesota at 44.85 N, 93.57 W with nearby profiler data, and station 74648 in Oklahoma at 35.68 N, 95.86 W with CEOP station in Morris and profiler data on site (see below for description of CEOP data).

The profiler data used were found at the nearest station with those data. Stations 74753, 74556, and 74341 were used for stations 72248, 74560, and 74341, respectively. These three stations have hourly profiler data, which includes the horizontal and vertical wind components, temperature, and humidity.

2) *Precipitation Data*

The precipitation data were obtained through Goddard Space Flight Center's TRMM Data Access. In specific, the '3-Hour 0.25° by 0.25° TRMM and other satellites rainfall' data product group (http://daac.gsfc.nasa.gov/data/datapool/TRMM/01_Data_Products/02_Gridded/06_3-hour_Gpi_Cal_3B_42/index.html) was used to view the observational precipitation for the months of June, July, and August in 2003 and 2004.

The precipitation file is a non-coARDS HDF file. Using GrADS (Grid Analysis and Display System) to display the data, each month was viewed individually to

find significant precipitation events, and those events were further analyzed to determine the exact times of precipitation to be used alongside other parameters. Specifically, the precipitation events closer to the evening hours were narrowed in on to research further for this project.

3) *CEOP Data*

CEOP (Coordinated Enhanced Observing Period) data were used to view the surface and flux parameters (http://data.eol.ucar.edu/master_list/?project=CEOP/EOP-1). Only two of the chosen stations, Bondsville and Okmulgee, were used in this research. This is due to the lack of scattered wind profiler stations in the Great Plains region. These two stations represent the central latitudes of the Great Plains.

The information that we examined from the CEOP data files includes hourly observations of soil heat flux, soil temperature, soil moisture, general surface meteorology, flux, and surface radiation data sets. These parameters in conjunction with the precipitation observations will be viewed to understand the tendencies of the boundary layer. In addition, some of the surface parameters were used to calculate the Lifting Condensation pressure level.

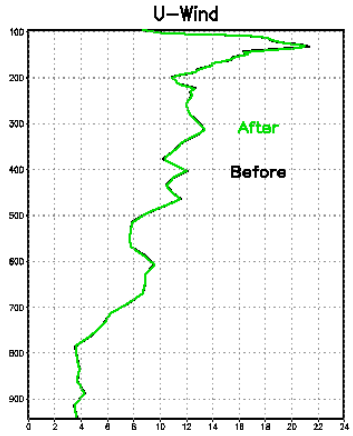
Using the data

Sorting data

The conventional data that was able to be opened inside of GrADS was first formatted through FORTRAN code to be to GrADS files, written by GMAO scientist Steve Bloom. This code also generated files for each of the atmospheric parameters, then further broken down into separate months. These files further broke down the Conventional data files into different meteorological parameters: temperature, specific humidity, and surface winds. This was done for ease of observing the data and to make the files more manageable.

In order to use the thousands of lines of conventional data acquired, it was necessary to sort through this data to find only the stations of interest in the Great Plains. A script was generated in order to sort through each month of data to use only data for the four sites in question. A script was made by GMAO member Tommy Owens to apply a filter to the conventional data files and pull out data only for the applicable stations used for this research. When these two steps were completed, each station had individual temperature, specific humidity, and surface wind data for six separate months (three months in two different years).

How the data was analyzed



As previously stated, GrADS was used to view all of the earth science data used in this research project. GrADS has the capability to open several different files at once to view different parameters. This proved to be an

advantage because there was a specific need to compare different datasets against others. A certain GrADS function, dfile, was used to accomplish this. The 'dfile' function allows the user to open several files at once, and then choose the necessary file to start displaying data. The user can then change the default file to the other parameter they wish to analyze, and display that data directly on top of the previous dataset. When finding the boundary layer looking at vertical profiles, it became very beneficial to use this function to display temperature, specific humidity, and winds against each other to find the layer.

Vertical Interpolations

In order for the radiosonde and wind profiler data to coincide with one another, the vertical levels for each had to be aligned. For this reason, a FORTRAN code was made to make the vertical levels for each of these datasets to match. A uniform set of pressure levels were selected to match the two sets.

These vertical interpolations were plotted against the original datasets to confirm how precise they were. Figure 1 shows the plotted vertical structures of each against each other. When tested, the vertical interpolation of both the radiosonde and wind profiler datasets captured the fine-scaled structure and undulations almost exactly.

Approach

There are several different theories as to why the models predict precipitation while sometimes no precipitation occurs, but at the peak of heat in the day, and precipitation then occurs later in the evening or nighttime hours instead. One possibility is that the low-level jet advects warm, moist air from the Gulf of Mexico to the central Great Plains region and stimulates turbulence and possible convection. This low-level jet appears in nighttime vertical wind profiles. The jet can become unpredictable; therefore the path of the jet is sometimes unknown. This could be slightly more difficult to integrate into model interpretations, and therefore cause the models to sometimes be incorrect.

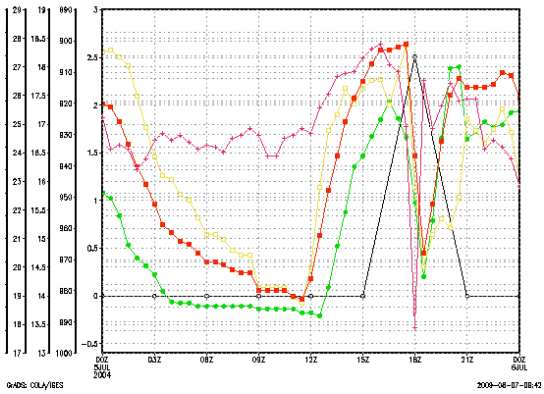
Another possibility is related to the correspondence between the Lifting Condensation Level (LCL) and the Boundary Layer (BL). The LCL is the point where the beginning stages of cloud formation is known to happen. The LCL is frequently known as the "cloud base", which is the point where, if an air parcel has enough energy to be transported up to, the parcel will begin to condense. Inside the BL, turbulence catches air parcels and directs them in multiple directions, making a well-mixed atmospheric boundary layer. If the BL somehow rises above the level of the LCL, the well-mixed, warmer atmospheric air inside of the boundary layer is transported up to the Lifting Condensation Level and is able to condense.

In order to find the LCL, a calculation was made using surface observations. The pressure level of the LCL is calculated using the following equation:

for warmer and moister air parcels to be transported to the LCL, the BL must be well-mixed. As stated in the "Analysis" section, turbulence is the driving force behind how "high" the BL will become. The turbulence kinetic energy (TKE) is the amount of energy behind the movement of these vertical winds, and that determines just how fast the BL grows. The definition of TKE is:

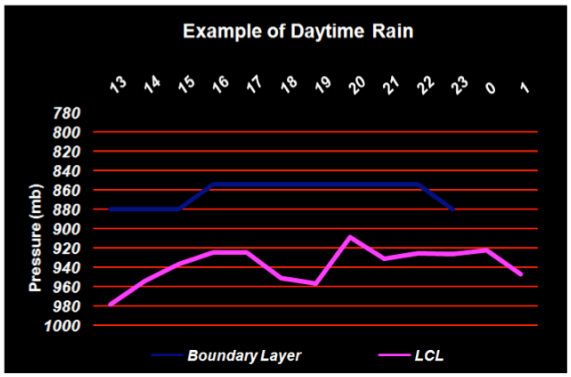
ide the boundary layer is raised above the LCL, and that air is able to condense at a rapid rate.

Daytime rain event associated with sudden drops in LCL, net radiation, and air temperature



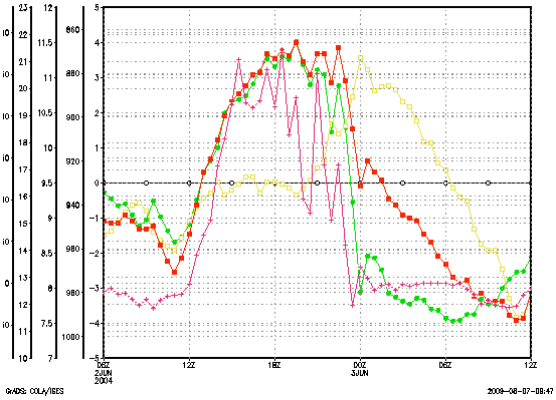
This rain event, occurring from 10 am (15Z) on 05 July 2004 to 4 pm (21Z) 05 July 2004, occurred during the peak air temperatures of the day. This event type is the typical prediction of the models; occurring during the highest surface temperatures and specific humidity of the day, which is most prone to lifting. Figure 10 shows the vertical profile of the atmosphere before, during, and after the event, and Figure 11 shows the BL/LCL relationship plot.

Figure 10 shows, to a certain extent, exactly what the MERRA would agree with. The air temperature and specific humidity begin to rise at sunrise (12Z), and when the air temperature is warm enough to induce lifting, condensation begins shortly after. It was necessary to look at an event like this to have a vertical visual of the atmosphere during a precipitation event.



As seen in Figure 11, the LCL begins very close to the surface in the morning before the event begins. This suggests that there is a dense layer of fog in the area that morning. The air temperature, as seen in Figure 10, rises significantly (approximately 18°C) in a period of 5 hours, then drops 10°C in about an hour. This may have been a cold front entering the area, and as a result, a thunderstorm occurred. In any case, the boundary layer stays elevated above the LCL for the extent of the day, which suggests that there was a considerable amount of mixing happening at and above the LCL.

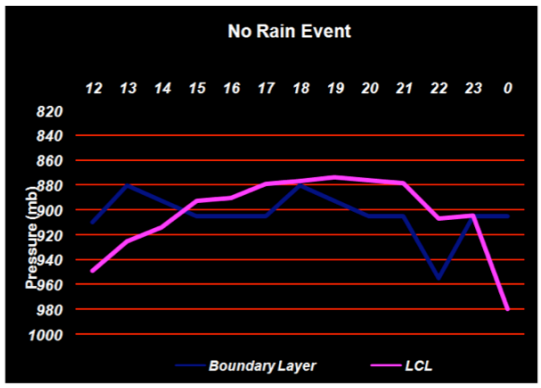
No rain event



As an example of what the boundary layer/LCL relationship looks like outside of a precipitation event, Figures 12 and 13 show the vertical profile of the atmosphere and BL/LCL relationship plot, respectively, of a 30-hour period with no precipitation.

As seen in Figure 12, the LCL and air temperature follow each other almost exactly through the peak temperatures of the day, with the net radiation following close behind. The LCL stays elevated during the daytime hours, and drops to a lower level following sunset. The specific humidity seems lower for the day as well, so the moisture in the atmosphere may not have been completely favorable for a rain event.

Figure 13 shows the BL/LCL relationship plot for this event. It is important to note that, during the peak temperatures in the day, the boundary layer stays below the LCL level. This shows that the mixed layer inside the atmospheric boundary layer was not able to reach the LCL pressure level, and therefore transported no warm, moist air to this level. Only after the peak temperatures have been reached does the boundary layer become elevated above the LCL. The LCL also stays at a higher level throughout the day than during a usual rain event. In typical rain events, the LCL can drop as low as 980mb. In this particular example, the LCL stays above 900mb for the peak air temperature periods of the day.



The combination of these results shows that the boundary layer and Lifting Condensation Level relationship does seem to have an effect on daytime precipitation, but does not seem to be a direct explanation for nighttime precipitation.

Conclusion

The extent of the research done during this term was the initial stages of a much more in-depth research project studying the affects the boundary layer has on precipitation. As seen in some of the cases shown above, the boundary layer may have an affect on precipitation by raising warm, moist surface air above the lifting condensation level; transporting warmer, moister air up to the level where condensation begins. By looking at plots that compare these two levels during the daytime, we can see that, when the boundary layer is elevated above the LCL, the warm and moist air in the mixed layer of the boundary layer is transported up to the Lifting Condensation Level, and precipitation occurs. During daytime hours, when the planetary boundary layer is below the LCL, there is no precipitation.

The variety of collected data to find these results aided significantly to the findings here. Each of the datasets was needed in order to understand these relationships better. The three stations that were focused on for this research all had information from these datasets to compare on. By first locating the stations in the Great Plains with all of the accessible data, all of the stations could be compared equally to get a greater understanding of the Great Plains' precipitation events. With further research, more of these stations can be compared to others to understand the entirety of the Great Plains.

Daytime precipitation events seemed to be explained well using the boundary layer and Lifting Condensation Level relationship. In the scenarios seen in the ‘Results’ section, daytime precipitation coincided exactly with the boundary layer being above the LCL. On the other hand, nighttime precipitation was more difficult to predict using this relationship only. Through further research, the nighttime precipitation events can be understood more, and that knowledge can be applied to perfecting the MERRA models.

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