Effects of Soil Moisture Variations on Summer Convective Activity over the Floridian Peninsula

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1. Introduction

Atmospheric moisture content plays a large role in day to day weather patterns across the planet. Meteorologists define air masses based on their temperature and moisture content to give a gross estimation of what type of weather to expect. However, air masses evolve depending on the surface it traverses. Several experiments the United States have shown that soil moisture has an apparent effect on average precipitation (Shukla and Mintz 1982; Oglesby and Erickson 1989; Chahine 1992a; Beljaars et al. 1996). Convection due to soil moisture heterogeneities in the Southern Plains has recently been studied (Frye and Mote 2010). The Floridian summer is synonymous with barotropic, pockets of convection unassociated with mid-latitude cyclones and their corresponding frontal boundaries. Subsequently, the mechanisms that create the diurnal weather patterns are local to the Florida climate. As a result, the current meteorological state of the region plays a significant part in the development of weather. This research investigates the relationship between 0-2 meter soil moisture and atmospheric moisture content during a sea-breeze event.

2. Background

Soil moisture plays a pivotal role in mesoscale weather system development in other areas of the US. Corn can play a significant role in the evapotranspiration and moisture transfer processes in the area around the crop (Howell et al 1996). That is, corn contributes to the overall moisture content of the lower atmosphere through evaporation. Low-level moisture is vital to the formation and evolution of convective clouds and precipitation. Soil moisture has been shown to have a positive relationship to evapotranspiration and several studies have linked soil moisture to precipitation and climate variations (Koster and Suarez 2001; Koster et al. 2004; Mo and Juang 2003). In recent years, soil moisture has become an important issue for computer models. The

Climate Prediction Center has a dedicated model to track and predict soil moisture (Huang et al. 1996; van den Dool et al., 2003). Soil moisture experiments have been limited in scope. Therefore, there is a need to expand this research to different regions and climates on the Earth.

Florida's unique geography and proximity to the ocean significantly affect diurnal weather patterns over the area. The peninsula frequently produces easterly and westerly sea breezes whenever there is a significant temperature gradient between the terrestrial and oceanic surface temperatures. When the two coastal sea breezes collide over central Florida, the resulting surface convergence produces upward vertical motion. Provided a conditionally unstable thermal profile, the sea breezes are often strong enough to initiate convection. Since the sea breeze is a low-level phenomenon, it is more susceptible to surface fluxes and forcings than larger, synoptic scale patterns. Soil moisture, similar to surface temperature, could potentially affect the intensity of the sea breeze convergence and promote increased upward vertical motion. However, several questions surround the interaction between soil moisture and the Floridian sea breeze. How rapid is the moisture transfer process between the surface and the lowest layer of the atmosphere? Will the additional water vapor picked up by the soil have an appreciable effect on the already moist maritime tropical air associated with the on-shore breeze? And perhaps most interestingly, how will solar radiation affect the soil moisture transfer process? Will the addition of soil moisture slow sensible heating at the surface as more energy is taken up by the evaporation process, thus weakening the thermal gradient and the sea breeze? This study seeks to shed some light on these issues through using idealized numerical weather prediction software.

The software package used is version 3.2.1 of the Advanced Research Weather Research and Forecasting model (WRF-ARW; Skamarock et al. 2008). This version contains several idealized cases available for compilation and modification. This study uses the idealized, two-dimensional sea breeze case for the experiments. Unlike some other idealized cases, the sea breeze option allows full physics schemes, making it ideal for studying surface-atmosphere interactions.

3. Experimental Design

The experiment uses a five-member ensemble to test the different soil moisture initial conditions. The domain is a 6-km wide, 664-km long slice stretching across Central Florida with a horizontal grid spacing of 2 km and 35 linearly spaced vertical levels, covering the surface to 19 kilometers. A 2-km grid resolution is used to capture the micro-scale phenomena that occur through the depth of the sea breeze front. The land mass consists of the middle 110 grid points which equates to a 220-km wide area of land. While this is a bigger area of land than the default setting for the model, the ratio between the size of the land mass and the size of the water around it is the same as the default ratio contained within the idealized sea-breeze case. The ensemble model uses the default Kessler microphysics scheme. The convective parameterization scheme is turned off to allow explicit convection and cumulus cloud development within the model. The soil physics scheme uses the Unified Noah land-surface model (hereafter, LSM). To test soil moisture sensitivity, all four soil levels, stretching from the surface to 2 meters deep, are varied uniformly as an initial condition to prevent unnecessary moisture transfer between the layers. Each soil layer is initialized at a constant 300 Kelvin. Ocean skin temperatures are set at 280 Kelvin to induce a healthy sea-breeze. 0-2 meter soil moisture is altered in each ensemble member to test the impact that variable has on atmospheric conditions including water vapor mixing ratio, low-level humidity, and zonal and vertical velocities.

Soil moisture is measured by the US Department of Agriculture's Soil Climate Analysis Network as a ratio of cubic meters of water to cubic meters of soil. There are only 3 stations in

Florida; one in the panhandle, one in central Florida, and one in the Everglades. Due to the lack of observations across the state, a useful database of Floridian soil moisture values could not be compiled for this study. Therefore, the moisture values used in this simulation are based on a saturation scale. According to Hydra Probe, the manufacturer of the soil moisture probe used by the Department of Agriculture, soil saturation, where water fills the pores between the soil, occurs between .3-.45 m^3m^{-3} depending on the type of soil. 50% saturation is defined as 1.875 m^3m^{-3}. Wet conditions are defined as the low end of the saturated scale .3 m^3m^{-3}. A dry initial condition is defined as 25% saturation and a drought condition is defined as 10% saturation. Lastly, a post tropical cyclone condition will contain super-saturated soil. Table 1 shows the soil moisture ratios used during the experiment for each model run.

Table 1					
Soil Moisture	Drought	Dry	50% sat.	Wet	Post-hurricane
m^3/m^3	0.02	0.0750	0.1875	0.3	0.6

Table 1.) Soil moisture values used in each soil layer across the land mass.

The experiment will initialize at 0000 local time June 1st 2012. Typically, airmass convective activity is at a minimum during the night. The time scheme allows for moisture transport during the overnight hours between the surface and the airmass above to test whether the soil can modify the atmosphere over a one night period using the Noah LSM. The simulation runs for 20 hours, outputting forecasts every 30 minutes. The forecasts between 1300 and 2000 local time are examined to determine the effect soil moisture has on the sea-breeze and the corresponding surface convergence in the middle of the land mass. Plots of vertical velocity, zonal velocity, humidity, cloud liquid water mixing ratio, and water vapor mixing ratio are analyzed using the National Center for Atmospheric Research (NCAR) Command Language (NCL) scripts for variations in intensity and coverage.

4. Results

Varying soil moisture using the Unified Noah LSM scheme has several interesting effects on sea-breeze characteristics. Looking at the 1000mb temperatures in each experiment (Table 2), experiments with higher soil moisture values warm more slowly and reach a lower maximum temperature than the drier experiments. This leads to a deeper boundary layer, and more vigorous mixing prior to sea-breeze convergence when soil moisture values are drier.

Table 2					
975mb Temp.	Drought	Dry	Middle	Wet	Post-hurricane
°Celsius	31	30	28	27	26

Table 2.) 975mb temperatures at the middle of the land mass at 1530 local time

Faster vertical velocities along the sea-breeze fronts accompany the warmer temperatures. Figure 1 illustrates the different vertical velocity fields during the mid-afternoon. Two separate sea-breeze fronts are easily resolved by their characteristic leading edge of strong vertical velocity on either side of the plot. Magnitudes of one meter per second and greater define the vertical motions associated with the drier soil whereas the moister soil experiments yield less impressive vertical motions during the same period. Examining the zonal wind field (Fig. 2) reveals further velocity differences between the model runs. The fastest horizontal winds associated with the sea-breezes occur in the drought (Fig. 2a) and dry (Fig. 2b) experiments. Also evident is an area of “noise” at the center of some vertical velocity plots. This phenomenon is a result of turbulent air stirred up by thermals, which spontaneously form when the environmental lapse rate meets or exceeds the dry adiabatic lapse rate. This area of thermal activity is prominent on the drought (Fig. 1a) and the dry (Fig. 1b) vertical velocity plots. However, the activity begins to taper off in the 50% saturation run (Fig. 1c) and is nonexistent in the more moist runs (Figs. 1d and 1e). This is consistent with the deeper boundary layer created by the drier conditions.

A cursory glance at the water vapor mixing ratio plots at 1630 local time (Fig. 3) reveals a sharp difference in moisture content in the lower atmosphere below 2000 meters. The model runs with drier soil (Figs. 3a and 3b) are much drier in the lower levels of the atmosphere than their more moist counterparts (Figs. 3d and 3e). Further inspection reveals that the moister experiments' high moisture values do not extend as high as the drier experiments (Fig. 3). This is consistent with the higher boundary layer and more pronounced thermal activity within the experiment runs with drier soil moisture.

Sea breeze convergence times are bookended by the drought experiment, which converges at 1700 local, and the post-hurricane experiment, that finally converges at 1800 local (Fig. 4). Vertical velocity is notably more intense at the moment of convergence in the drought case (Fig. 4a) than the post-hurricane run (Fig. 4e). However, the vertical motions associated with the drier cases quickly subside within 30 minutes (not shown) whereas the vertical wind profile in the post-hurricane case develops over the next hour displaying relatively robust updrafts and downdrafts in the convergence zone. Only after 1900 local does the vertical wind return to nominal, pre-convergence activity (Fig. 5).

The relative humidity values remain below 80% in all the experiments until the sea-breezes begin to converge (not shown). This pattern is mirrored by the cloud liquid water mixing ratio. Therefore, relative humidity will be used in order to represent the possible cloud envelope within the domain. All cases have a similar high humidity field develop at the beginning of the convergence process (Fig. 6). A notable element of 98% humidity appears around 3000 meters. There is a slight variation in the height of the element between the simulations with the dry runs

(Figs. 6a and 6b) developing the area of high humidity at a slightly higher altitude than the moist runs (Figs. 6d and 6e). However, this slight increase in altitude is not indicative of a more robust updraft, but is a result of the higher boundary layer present in the drier cases. All of the relative humidity elements begin to widen and dissipate with time (not shown). However, the post-hurricane humidity element strengthens for about an hour and spreads upward in a slender column to about 7000 meters before mixing away (Fig. 7). Water vapor concentrations follow a similar pattern (not shown). Interestingly, the 50% saturation run contained the smallest high humidity elements at the experiment end time of 2000 local time (not shown).

5. Relation to Other Work

This study seeks to understand the sea breeze sensitivity to soil moisture. Baker et al. 2001 analyzed soil moisture, coastline curvature and land breeze circulation and their effects on sea breeze-initiated precipitation using the Goddard Cumulus Ensemble Model. The study found that soil moisture acted as a source of atmospheric moisture and promoted instability in the atmosphere. As a result, precipitation was locally heavier around areas of high soil moisture content. This agrees the findings of Crook 1996 and Eltahir 1998.

Strong, sustained, upward vertical motions promote cloud growth and precipitation. Since these robust updrafts were only displayed in the super-saturated post-hurricane case this study partially supports the findings of Crook 1996, Eltahir 1998, and Baker et al. 2001 that increased soil moisture values have a positive effect on precipitation accumulation. However, this study also suggests that if sea-breeze convergence does not occur, drier soil moisture values maximize atmospheric instability and could lead to stronger vertical motions.

6. Future Work

It is important to note that this study does not take into account longitudinal variations in vegetation and soil composition. A future model could take into account soil composition variations across the width of the Floridian peninsula. In addition, soil moisture was held constant across the entire land domain of the model as well as through the four layers of the soil moisture model. This study did not analyze soil moisture fluxes between the soil layers as the top soil layer lost water to the atmosphere. Furthermore, this research only uses the Kessler microphysics scheme. Other microphysics options may yield different humidity fields and vertical velocity profiles.

Additional research must be done to fully understand the soil moisture flux process and how that changes with different vegetation and soil composition. Also, similar studies to this one using a variety of sounding profiles should be done to determine if these findings hold true for all types of thermal and synoptic patterns. The domain of this model only represents central Florida. For a more comprehensive study of the Floridian sea-breeze, a full three dimensional model should be used to accurately represent the southerly sea-breeze and its effects. Lastly, the changes in surface emissivity and absorption with variations in soil moisture were neglected. Further research is needed to determine if the dry soil has similar radiation characteristics as the moist soil.

7. Conclusions

This study concludes that soil moisture values have a significant impact on the strength of the Floridian sea-breeze. The sea-breeze is a thermally-driven phenomenon and is regulated by the temperature gradient between a land mass and the surrounding water. The warmer, rising air over land creates a local low pressure center and air from over the sea rushes in to maintain equilibrium. This accounts for the direct correlation between higher 1000 hPa temperatures and faster zonal surface winds. The greater the temperature difference, the greater the pressure gradient between the land and the sea and higher wind velocities are expected.

We see that the atmosphere above moist soil does not warm at the same rate, or to the same degree as above dry soil. The only source of thermal energy within the model is the radiation emitted from the Sun. Therefore, the discrepancy in low-level warming can be attributed to solar energy transforming into latent heat rather than sensible heat. As solar rays strike the moist soil, water within the soil absorbs the energy and evaporates, leaving less solar energy to be converted into heat energy to warm the surface and the surrounding air. However, dry soil does not have many liquid water molecules to evaporate. Therefore, more solar radiation is transformed into sensible heat and more heat energy is released into the atmosphere. The corresponding expansion associated with warming air aids in deepening the boundary layer beyond the depth of the moist soil cases (Fig. 3).

The sea-breeze convergence provides a forcing mechanism to lift and cool the low-level air, thus promoting cloud and precipitation growth. While the sea-breezes in the drier cases converge with more velocity than the moist cases, the resulting updraft of the post-hurricane case provides the most promising vertical structure for significant cloud development. This is due to the amount of moisture the super-saturated case brought up to the mid-troposphere. The water vapor mixing ratio of the super-saturated case shows that the low-level air above the ground was much more humid than in the other cases. Values of 10 grams of water vapor per kilogram of air were seen only in the post-hurricane model run (Fig. 3e). Once the sea-breezes converged, the moist, low-level air was able to rise, generating clouds. However, once the air parcel got above 3000 meters, the air around it was significantly drier than in the lower levels. As the parcel rose, dry air is entrained into the updraft, effectively dehumidifying the air parcel. In the drier cases, the condensed cloud particles evaporate due to the dry air entrainment process, but in the super-saturated case, the updraft has sufficient moisture to punch through the dry air while maintaining high humidity values until about 7000 meters (Fig. 7). However, it should be noted that the wet case did not sustain an updraft or produce high values of humidity above 5000 meters. This suggests that a certain critical value of soil moisture is needed in order to overcome the dry air entrainment process and produce significant vertical motions in the convergence zone for this particular case.

This study found that a 20-hour period beginning at midnight is enough time for the ground to sufficiently modify both the temperature and the moisture content of the air above it to have a measurable impact on the daily sea-breeze. Drier soil conditions favor a deeper boundary layer and additional surface heating. Dry soil also promotes vertical motions within the boundary layer and enhances the velocity of the sea breeze. Moist soil tends to stunt the growth of the boundary layer and obstructs vigorous mixing in the lower atmosphere prior to sea-breeze convergence. Low-level temperatures are also kept lower by the broader distribution of solar energy between sensible heating and the energy required for the evaporation of water in the soil. However, given sufficient soil moisture, such as that found after a significant rain event, and sea breeze convergence, moister soil can lead to a drastic increase in instability and an increase in clouds in the sea-breeze convergence zone. Higher precipitation could be expected in the area. Soil moisture plays a significant part in controlling the Floridian sea-breeze, but unless the sea-breeze is strong enough to converge and there is an overabundance of water in the dirt, high soil moisture may not provide a positive influence on the development of strong, sustained updrafts.

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Figures

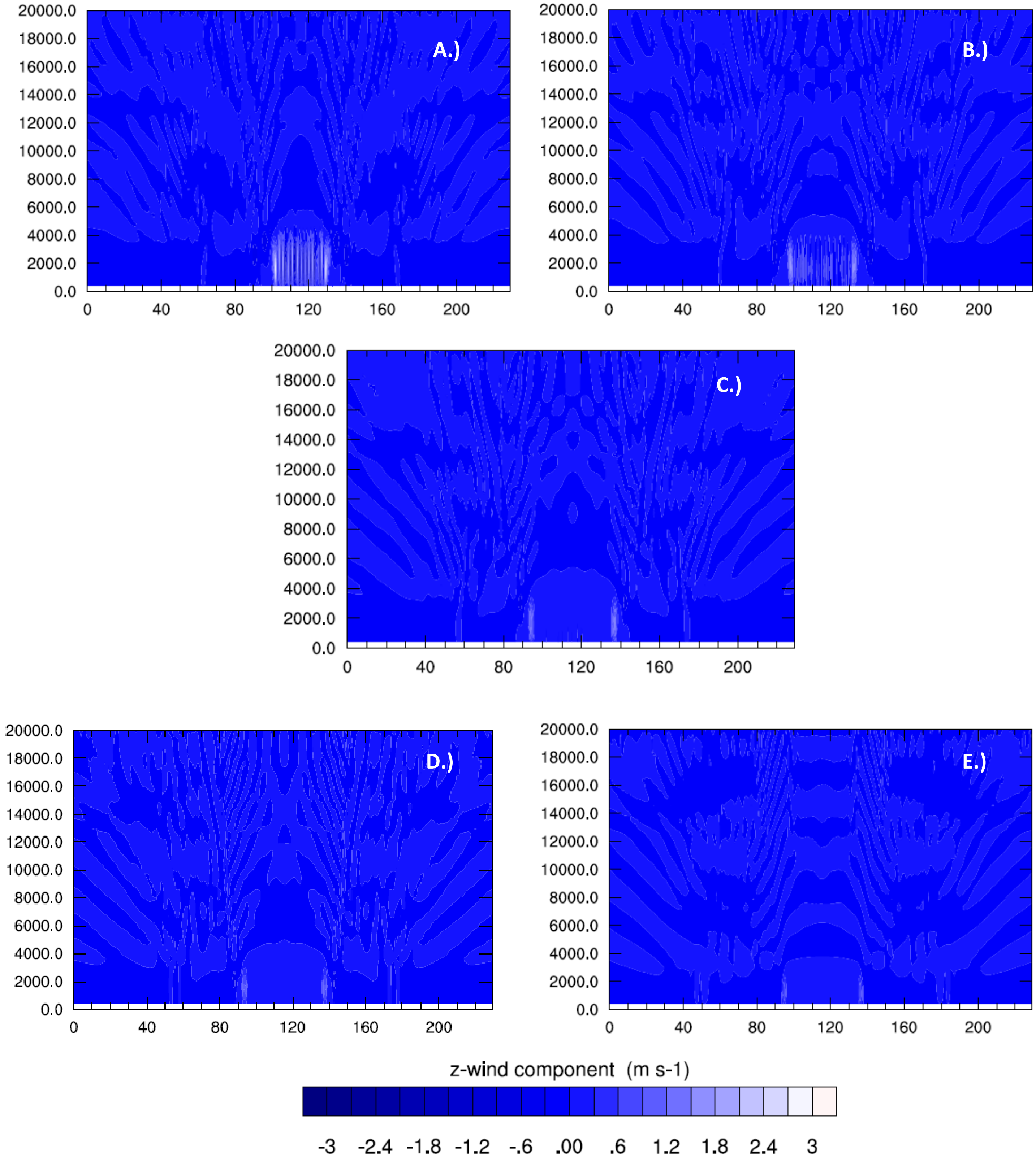

Figure 1.) Vertical wind velocities across the land portion of the model domain at 1530 local time. Altitude in meters is displayed on the vertical axes.

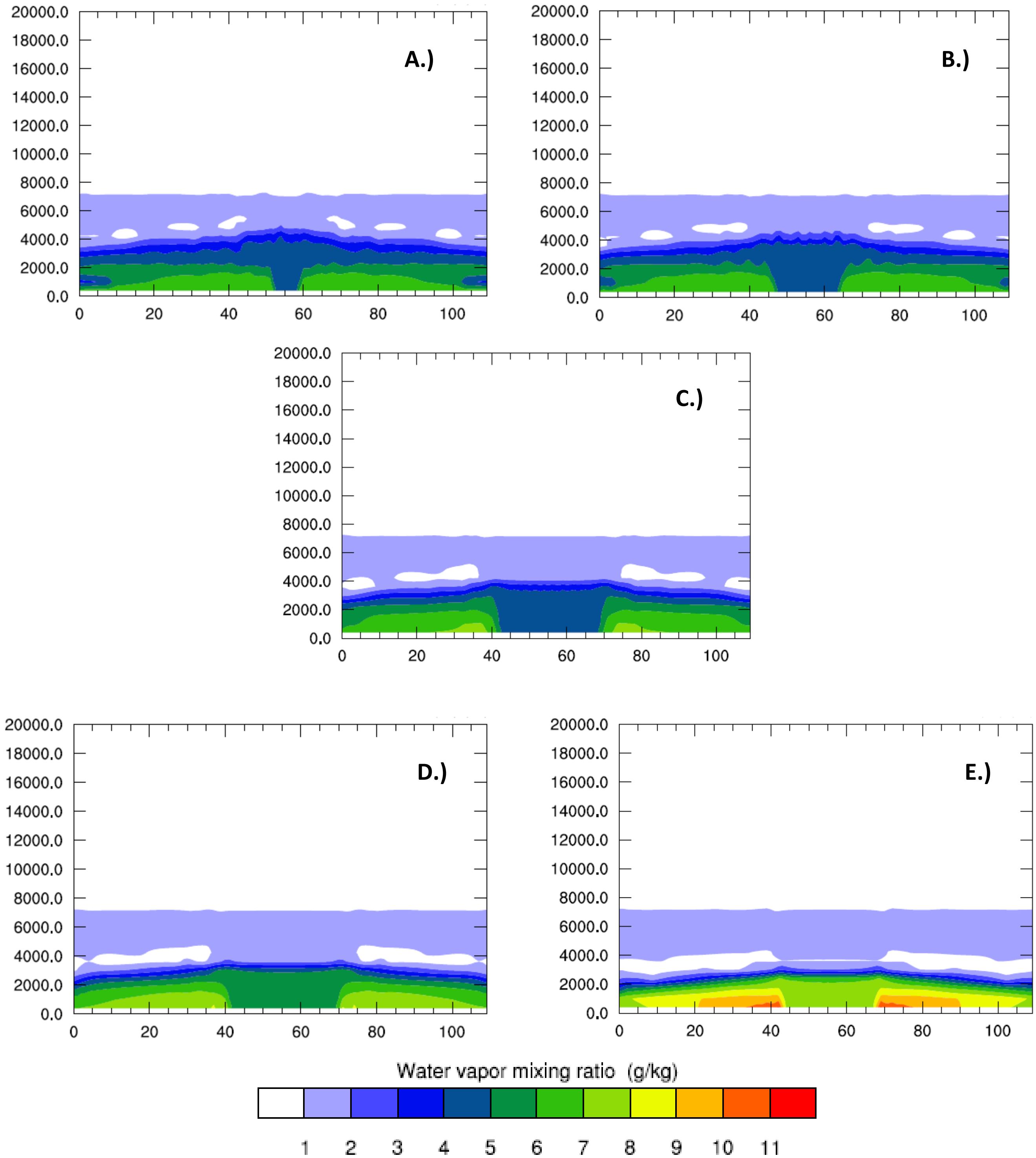

Figure 3.) Water vapor mixing ratio across the land portion of the domain at 1630. Altitude is displayed in meters on the vertical axes.

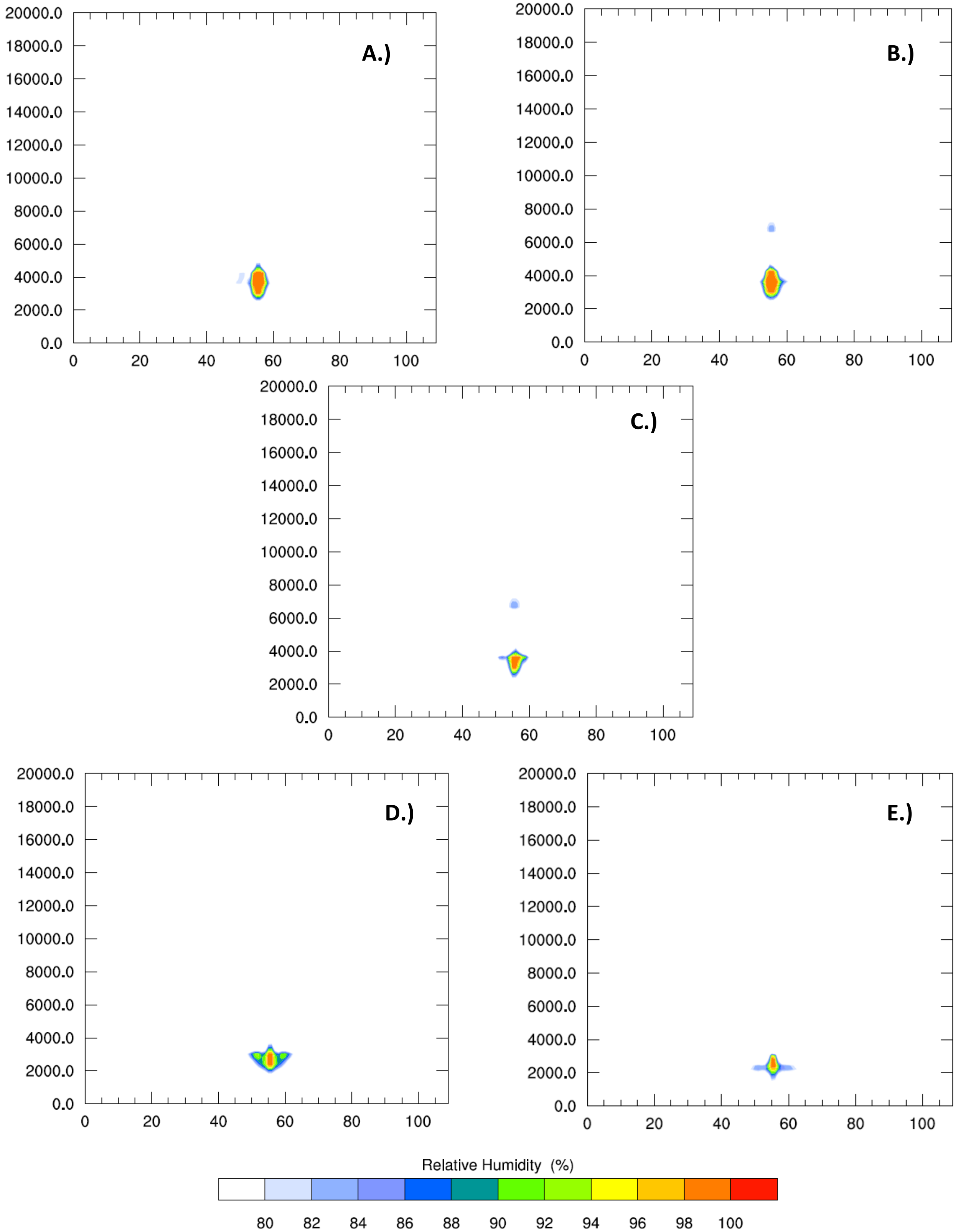

Figure 6.) Relative humidity percentages at the time of sea-breeze convergence over the land portion of the domain in each model run is displayed. Altitude is depicted in meters on the vertical axes.

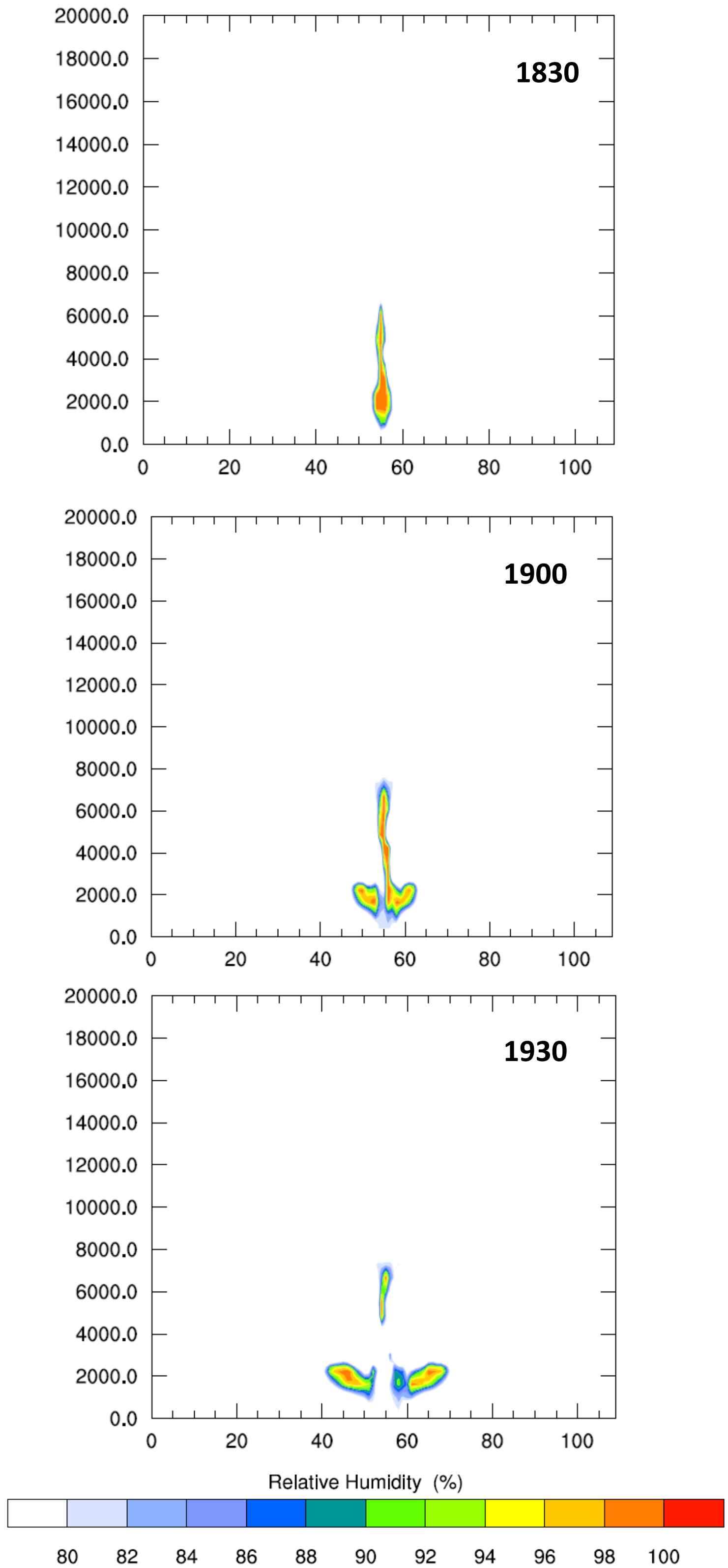

Figure 7.) Relative humidity for the post-hurricane case at 1830, 1900, and 1930 local times. Altitude in meters is displayed on the vertical axes.

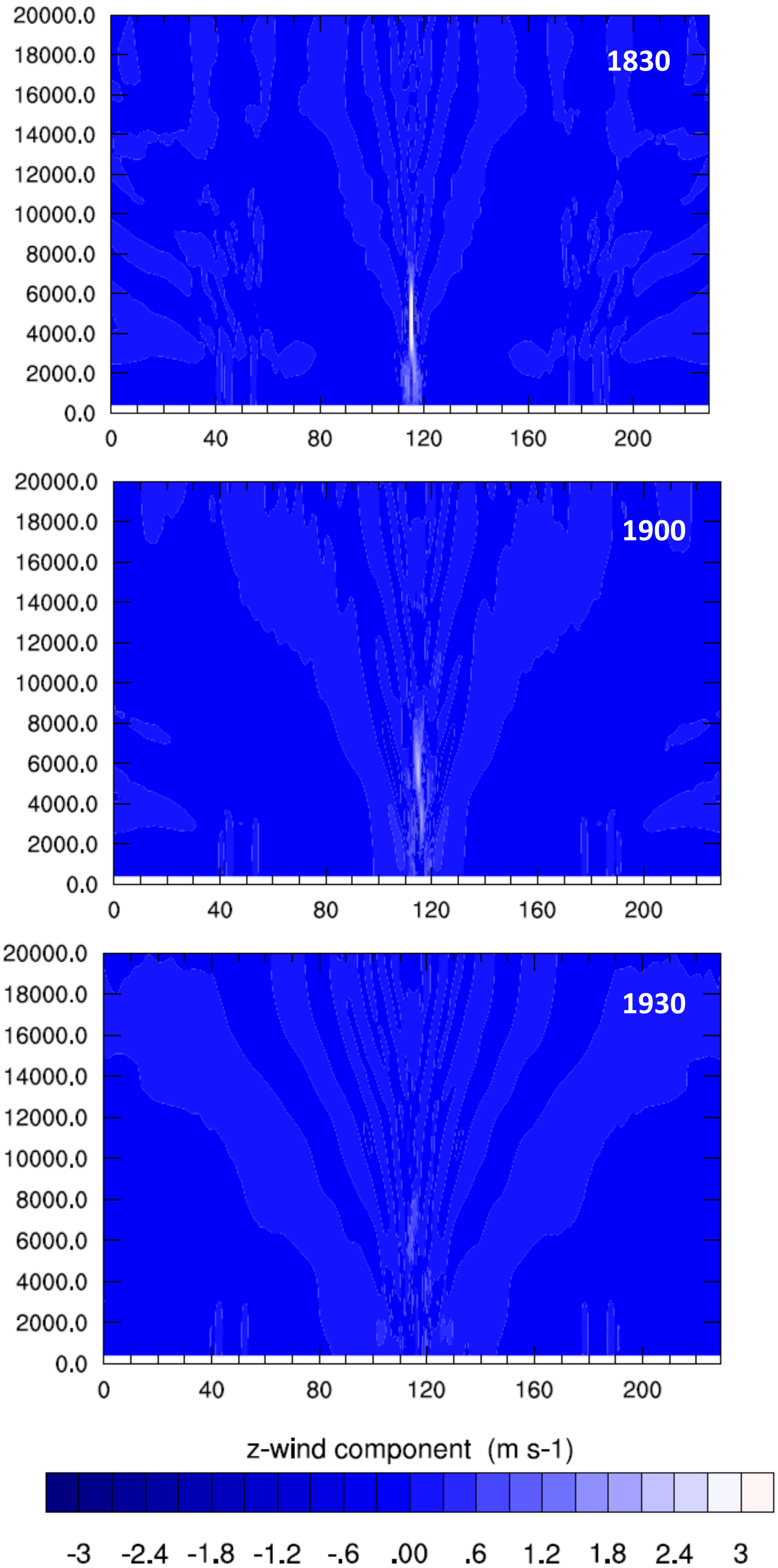

Figure 5.) Vertical velocity of the post-hurricane case at 1830, 1900, and 1930 local times over the land portion of the domain. Altitude in meters is displayed on the vertical axes.

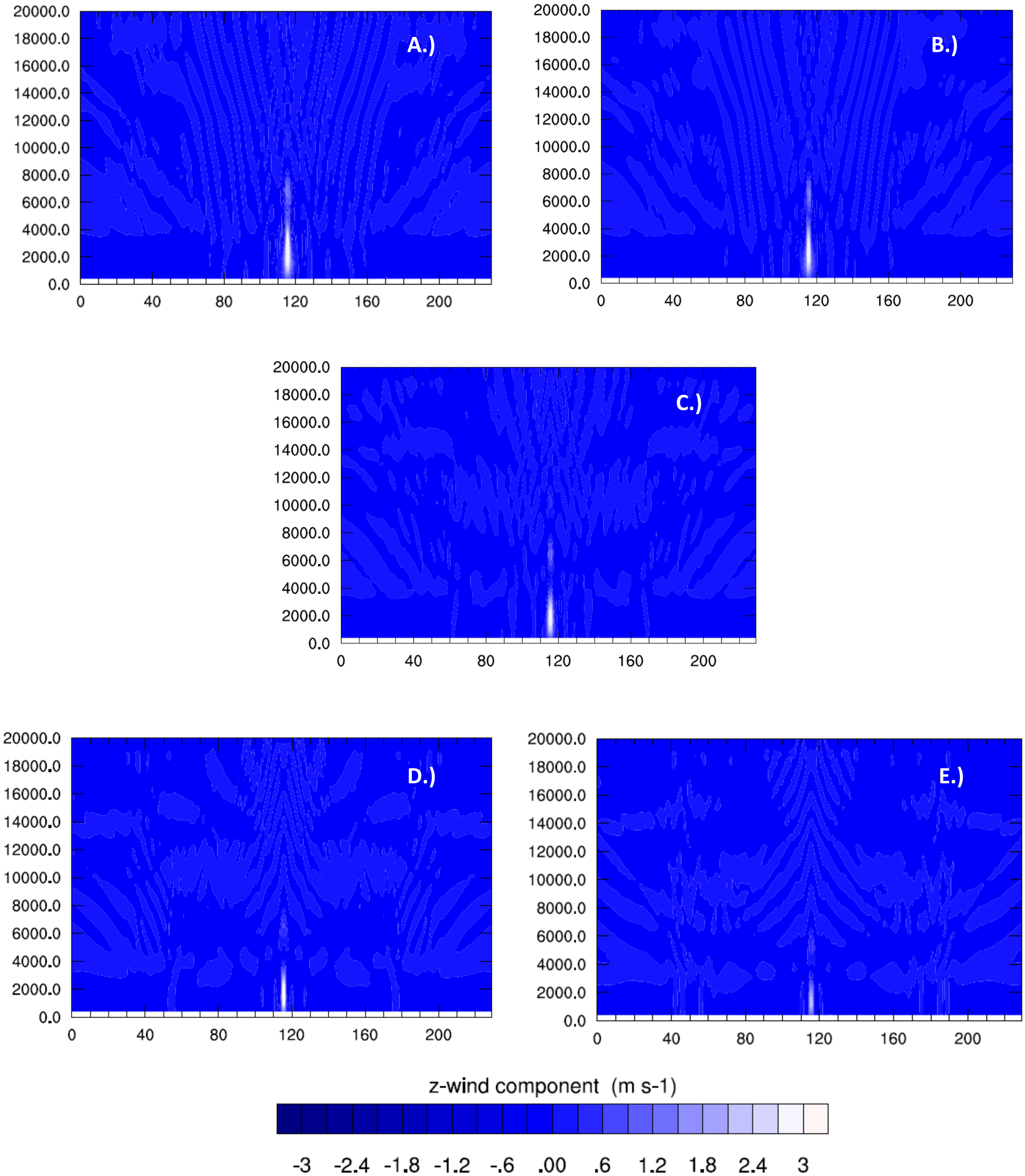

Figure 4.) Vertical velocity at each experiments' convergence time across the land portion of the domain. Altitude in meters is displayed on the vertical axes.

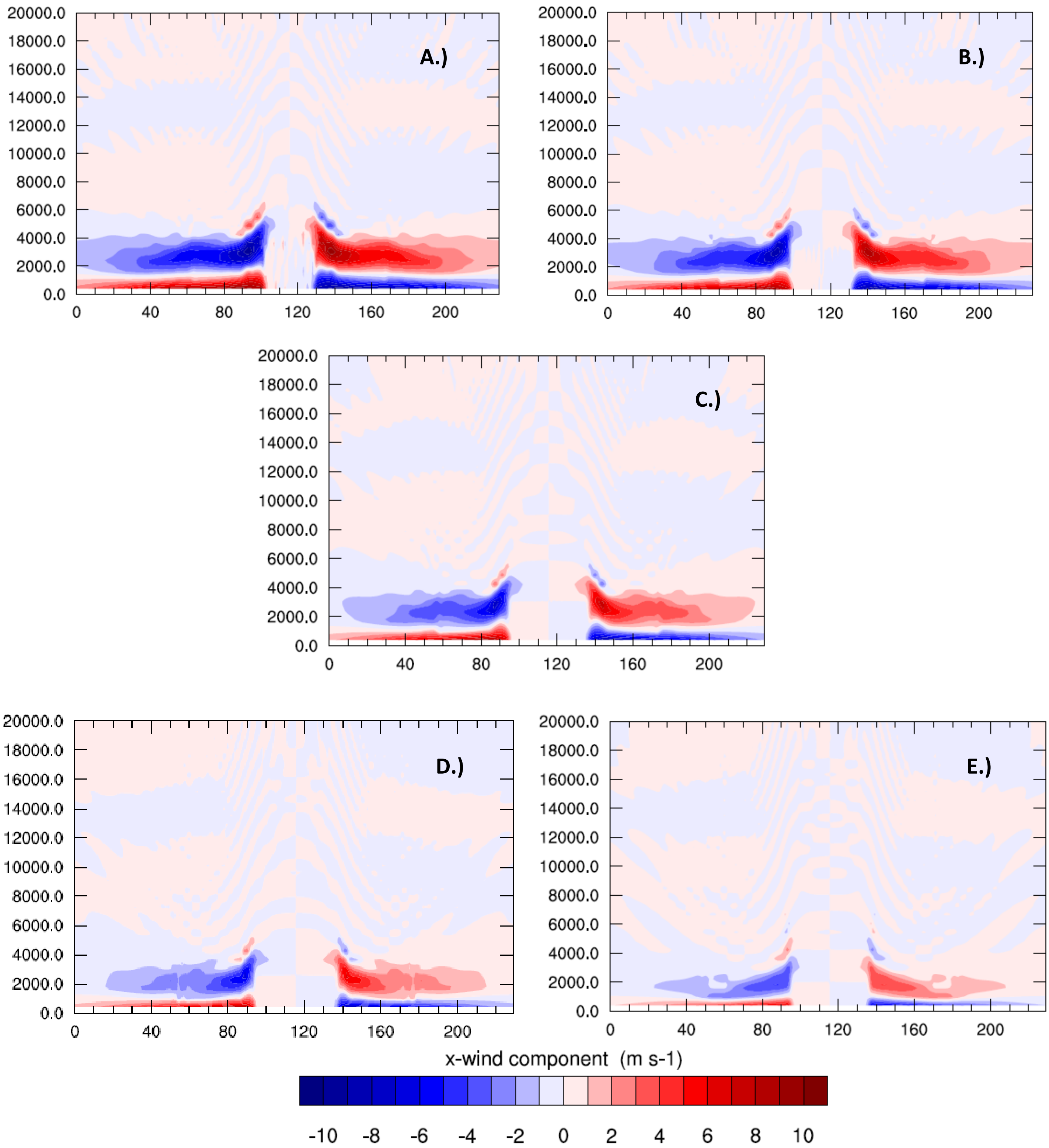

Figure 2.) Horizontal wind across the land portion of the domain at 1530 local time. Altitude in meters is displayed on the vertical axes.