Influence of Irrigation on Diurnal Mesoscale Circulations: Results from GRAINEX

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Key Points

• First extensive observational study of modification of slope wind circulations by irrigation

• Presence of irrigation in upslope regions weakens terrain-induced baroclinicity

• Irrigation-reduced baroclinicity weakens the afternoon slope wind circulation
Abstract

In order to understand the impact of irrigation on weather and climate, the 2018 Great Plains Irrigation Experiment collected comprehensive observations straddling irrigated and non-irrigated regions in southeast Nebraska. Using these observations, we examine how irrigation affects diurnal terrain-generated slope circulations, specifically the slope wind. We find that irrigation applied to upslope regions of gently sloping terrain reduces terrain-induced baroclinicity and the associated pressure gradient force by up to two-thirds. This leads to the reduction in the afternoon and evening upslope wind and is supported through comparisons to the High-Resolution Rapid Refresh (HRRR) operational model, which does not explicitly account for irrigation. Additionally, the presence of irrigation decreases daytime sensible heat flux (Bowen ratio reduced 40% compared to non-irrigated regions), weakening turbulent transport of momentum. Modifications to the terrain-forced circulation by irrigation has the potential to affect moisture transport and thus cloud and precipitation formation over the Great Plains.

Plain Language Summary

Agricultural irrigation alters input of heat and moisture from the land surface to the atmosphere, which can affect weather and climate. Irrigation is expanding on all continents except Antarctica and is thus a major pathway through which humans impact the environment. However, the observations required to study the mechanisms though which irrigation affects weather and climate are lacking. The Great Plains Irrigation Experiment (GRAINEX) was conducted to collect such observations near the boundary between irrigated and non-irrigated regions in southeast Nebraska. During the daytime, the slope of the Great Plains causes near-surface
upslope winds and downslope winds in the atmosphere above. At night this pattern reverses. This wind system influences storm formation by forcing upward motion and transporting moisture. Using the observations from GRAINEX and comparing to a weather model we find that irrigation weakens this wind system, potentially affecting cloud and rain formation in this region.

**Keywords**

Irrigation, slope wind, Great Plains, GRAINEX, mesoscale circulation, boundary layer

### 1 Introduction

In the modern agricultural economy, irrigation is a crucial practice that increases crop yields and extends arable land into semi-arid and arid regions (Zohaib & Choi, 2020). While globally only 20% of farmland is irrigated, such regions account for 40% of food production (Decker et al., 2017). Further, irrigation represents the largest burden on the fresh water supply, being over 70% of annual demand (Cai & Rosegrant, 2002), and is expected to expand on every continent except Antarctica (Zohaib & Choi, 2020). Irrigation substantially modifies all aspects of the hydrologic cycle including soil moisture, precipitation, and surface moisture fluxes (Huber et al., 2014; Kang & Eltahir, 2019; Sridhar, 2013). The atmospheric responses to irrigation, however, are complex and vary in both time and space (Cook et al., 2011; D. Lobell et al., 2009).

Much work has been devoted to understanding the atmosphere’s response to widespread irrigation, and the topic remains an area of active research. Irrigation modifies soil moisture both locally and remotely through precipitation downwind of the irrigated region (Barnston & Schokedanz, 1984; Deangelis et al., 2010; Kang & Eltahir, 2019; Lawston et al., 2017; Moore &
Moreover, irrigation reduces the Bowen ratio (the ratio of sensible to latent heat flux), producing additional atmospheric responses that include: reducing daytime surface temperature and increasing nighttime temperature (Lobell & Bonfils, 2008; Sorooshian et al., 2011; Sridhar, 2013), increasing atmospheric pressure (Kang & Eltahir, 2019), and modifying planetary boundary layer (PBL) and regional wind fields (Fast & McCorcle, 1991; Huber et al., 2014; McPherson, 2007; Ookouchi et al., 1984; Yang et al., 2020). The strength and sign of these responses vary widely depending on the degree to which the surface energy budget is water or energy limited prior to the onset of irrigation. (Cook et al., 2011).

One type of PBL circulation that may be modified by irrigation is the Great Plains slope wind. These winds are a diurnal mesoscale circulation that form due to differential atmospheric heating caused by the east-west slope of the Great Plains (Holton, 1967; McNider & Pielke, 1981). During the day, surface heating produces greater column warming in higher elevation (upslope) regions due to enhanced convergence of sensible heat flux. This produces a positive pressure perturbation and downslope winds aloft. Within the PBL, a compensating upslope wind forms. This process is reversed in the nocturnal PBL (McNider & Pielke, 1981; McNider & Pielke, 1984).

The Great Plains slope wind and its associated baroclinicity and boundary layer structure are known to be factors in the formation and evolution of the Great Plains low-level jet (LLJ) (Campbell et al., 2019; Gebauer & Shapiro, 2019; Holton, 1967; Lemone et al., 2014; Parish, 2017; Poulos et al., 2002; Sun et al., 2016). Additionally, convergence associated with mesoscale
circulations influences convective initiation (CI) (Barthlott et al., 2006). As the LLJ and CI both contribute to the rainfall distribution of the Great Plains, the slope wind is an important factor for regional climate. Baroclinic circulations like the slope wind also transport pollutants, which may have social and environmental consequences. The intensity of the slope wind, however, depends substantially on surface baroclinicity and PBL thermodynamic structure (Souza et al., 2000; De Wekker & Kossmann, 2015). Thus, irrigation may modify the climate of the Great Plains and similar regions with significant baroclinic circulations (conceptualized in Figure 1).

Despite considerable work by previous studies, there remain gaps in understanding the interactions between irrigation and mesoscale circulations such as the slope wind. Most studies that address the effects of irrigation (and soil moisture) on mesoscale circulations are theoretical in nature or utilize relatively coarse analysis grids that often poorly represent mesoscale phenomena (e.g. Anthes, 1984; Arcand et al., 2019; Campbell et al., 2019; Huber et al., 2014; Kueppers & Snyder, 2012; Ookouchi et al., 1984; Yang et al., 2020). This paper proposes to fill this gap using the extensive rawinsonde observations collected during the 2018 Great Plains Experiment (GRAINEX) (Rappin et al., 2021) in Nebraska to characterize the impacts of irrigation on the Great Plains diurnal slope wind. Specifically, this paper seeks to:

1. Characterize the Great Plains slope wind before and after the onset of irrigation,
2. Understand the impacts of irrigation on thermodynamic structure of the PBL and surface baroclinicity, and
3. Attribute modification of the Great Plains slope wind to irrigation.
The remainder of this paper is organized as follows: the datasets and methodologies used during the study are presented in section 2; the results are in section 3; and the implications and conclusions of the work are in section 4.

2 Methodology

Observations collected during GRAINEX, conducted during the growing season of 2018 in southeast Nebraska (Figure 1), are used to isolate the slope circulations and investigate how they are modified by irrigation. GRAINEX consisted of two Intensive Operation Periods (IOPs): May 29th-June 16th, 2018 (IOP 1) and July 17th-30th, 2018 (IOP 2) with reduced observations between those periods (Rappin et al., 2021). IOP 1 corresponds to the early growing period, when irrigation is limited, and IOP 2 occurs during the mid-growing season, which is characterized by vigorous crop growth and substantial irrigation. The GRAINEX domain (~100x100 km) straddles the boundary between irrigated and non-irrigated croplands with irrigation being dominant west of longitude 96.9 °W.

To characterize strong land and atmospheric gradients induced by irrigation, an extensive observation network was deployed, including rawinsondes from 5 locations launched bi-hourly beginning at dawn (0500 LST, 1100 UTC) and ending at dusk (1900 LST, 0100 UTC ) during both IOPs. Additionally, 12 Integrated Surface Flux System (ISFS) stations (see Supplemental Text S1), 2 Integrated Sounding Systems (ISS), 3 Doppler on Wheels (DOW), and 75 mesonet stations were deployed (Rappin et al., 2021). This study focuses on the analysis of rawinsondes released approximately along a west-east transect that includes ISS 2 (eastern site), DOW 6 (central site), and ISS 3 (western site). Note that these rawinsondes sample atmospheric conditions affected by land surface heterogeneity due to both gently sloping terrain and time
varying irrigation effects in the western half of the transect. Surface energy fluxes from ISFS stations are used to characterize land-atmosphere interactions under the effects of irrigation.

Similar to prior baroclinic circulation studies (e.g. Souza et al., 2000), circulations induced by land surface heterogeneity (terrain & irrigation) are isolated by negating daily averages of horizontal wind components as a function of altitude from corresponding bi-hourly rawinsonde observations. Mathematically:

$$u(z, t)' = u(z, t) - \bar{u}(z); \quad v(z, t)' = v(z, t) - \bar{v}(z)$$  \hspace{1cm} (1)

Where $u$ is zonal wind, $v$ is meridional wind, $z$ is altitude, and $t$ is time at a specific location. The bi-hourly perturbation profiles are averaged at each site for a selected set of case days during each IOP. This procedure yields mean bi-hourly perturbation wind profiles for the three sites during each IOP. Perturbation wind speed is then computed from the perturbation wind components.

In the above-described decomposition, diurnal variation of the perturbation wind within the PBL is modulated by turbulent mixing of momentum and heat, while the mean wind profile is determined by the synoptic scale pressure gradient force (PGF). In order to compute the diurnally varying portion of the PGF, which is induced by differential heating along the transect, perturbation pressure is calculated for each sounding site as follows:

$$p(z, t)' = p(z, t) - \bar{p}(z)$$  \hspace{1cm} (2)

where $p$ is pressure and the bar and prime denote the daily mean and perturbation from that mean respectively. The diurnally varying perturbation PGF is then calculated using a centered difference over the domain:
\[ PGF(z, t) = -\frac{1}{\rho} \frac{p'_{east}(z, t) - p'_{west}(z, t)}{\Delta x} \]  

(3)

where east and west correspond to ISS 2 and 3 respectively and \( \Delta x \) is the distance between those stations (~100 km). Since irrigation impacts baroclinicity through alteration of PBL temperature and moisture, average bi-hourly altitudinal profiles of virtual temperature (\( T_v \)) are also analyzed for the case days during each IOP.

In addition, we also compare results from the above-described analysis to corresponding simulated fields from the 3 km grid-spacing High Resolution Rapid Refresh (HRRR) operational model analysis (Benjamin et al., 2016; Blaylock et al., 2017; Lee et al., 2019). The above-described wind and PGF decomposition are repeated for each rawinsonde launch location using HRRR-simulated profiles at the closest grid point. Note, that while the HRRR analysis implicitly incorporates some effects of irrigation through assimilation of in-situ and remote sensing observations, explicit effects of enhanced soil moisture fluxes are not represented due to the lack of irrigation parameterization. Indeed, this is validated by comparison of ISFS sensible and latent heating observations to HRRR simulated values (Supplemental Text S2). Thus, the differences in diurnal evolution of perturbation winds and PGF between observations and the HRRR analysis are used to evaluate the effects of irrigation on PBL circulations.

To minimize the impact of cloud cover on analysis, the selected set of case days for each IOP is limited to those with low cloud cover based on GOES-16, ISFS, and HRRR data (5 days in IOP 1 and 4 days during IOP 2; Supplemental Table S1/Figure S1). Further, National Weather Service Advanced Hydrologic Prediction Service (AHPS) historical precipitation totals (Lawrence et al., 2003) show that rainfall in the irrigated and non-irrigated regions is similar
(within one standard deviation) during both IOPs. Thus, the effects of irrigation are isolated from those of varying cloud cover and rainfall.

3 Results and Discussion

Because the focus of this study is modification of PBL circulations by irrigation, the following discussion is restricted to below 2000 m above ground level (AGL). The dominant pattern of perturbation wind within the PBL during both IOPs is transition to downslope in the early morning before decelerating as the PBL grows during the day. In the afternoon and evening, the PBL perturbation wind reverses to become upslope. Analysis of perturbation virtual potential temperature and perturbation vertical pressure gradient force (PGF) indicate that hydrostatic balance is applicable (Supplement Text S3). Thus, the dominant factors that influence the diurnal evolution of the PBL perturbation winds are diurnal variation of the PGF and turbulent mixing of momentum.

While the general behavior of the perturbation winds are similar between the two IOPs, there are differences in intensity and local vertical structure. Early morning perturbation wind speeds (Figure 2) are typically greater during IOP 1 than IOP 2 (generally 3-4 m s$^{-1}$ versus 2 m s$^{-1}$) and have a much deeper maximum (~500 versus ~200 m). This is consistent with the greater PGF during IOP 1 compared to IOP 2 (maximum of 4E-4 m s$^{-2}$ versus 2E-4 ms$^{-2}$) at 0500 LST (Figure 3). The orientation of the morning perturbation wind during IOP 1 is predominantly westerly during IOP 1, but in IOP 2 the perturbation wind below 1000 m AGL backs with height, shifting from easterly near the surface to west-northwest at 1000 m. Notably, the perturbation PGF is
consistently westerly below 1500 m AGL during both IOPs, suggesting that other processes are responsible for the turning of the dawn perturbation wind.

The above-described differences affect the evolution of two perturbation wind features that are present during the early morning (0500 LST; 1100 UTC) of both IOPs: MS1 and MS2 (here M denotes morning and S the surface during IOPs 1 and 2; Figure 2) and MA1 and MA2 (here A denotes atmosphere; Figure 2). The nature of these features depend on the conditions that exist during the previous evening at the onset of PBL decoupling, and their evolution is governed by such nighttime processes as the inertial oscillation and differential cooling along the slope. In fact, the initial development of MS1, MS2, MA1, and MA2 is observable in the perturbation wind analysis at 1900 LST for features ES1, ES2, EA1, and EA2 (where E denotes evening during IOPs 1 and 2; Figure 2). The evening perturbation winds in turn are dependent on the vertical mixing of momentum during the daytime and diurnal variation of the PGF and baroclinicity. The upslope perturbation winds at 1900 LST are stronger during IOP 1 due to both the enhanced zonal PGF (especially in the lower PBL at ES1 and ES2; Figure 3c) and vertical mixing of momentum. The greater vertical mixing during IOP 1 is driven by a combination of higher sensible heat flux (Supplement Figure S2) and reduced atmospheric stability (Supplement Figures S2 and S3). In fact, ISFS observations show a mean daytime Bowen ratio of 0.39 and 0.58 over the irrigated and non-irrigated areas respectively (Supplement Table S2), while the HRRR shows 0.42 and 0.77. The greater Bowen ratio in the model indicates that the HRRR is converting additional energy into sensible heating and consequent buoyant generation of turbulence.
Irrigation plays a role in reducing the magnitude of both the zonal PGF (Figure 3c) and vertical mixing of momentum during IOP 2. Higher soil moisture during IOP 2 produces shallower, but stronger nocturnal inversions compared to IOP 1 (Figure 4). The greater stability near the surface in combination with reduced Bowen ratio over the irrigated upslope region (Supplement Table S2) reduces the impact of differential heating along the slope, weakening generation of baroclinicity. Indeed, profiles of $T_v$ differences across the GRAINEX domain indicate reduced diurnal variability of baroclinicity during IOP 2 (5.0 °C versus 4.5 °C near the surface; Supplemental Figure S3a and S3c). Reduced baroclinic variability subsequently reduces the diurnal range of the PGF during IOP 2. This combined with reduced sensible heat fluxes over the irrigated regions, and correspondingly weaker vertical mixing, produces weaker upslope winds in the late afternoon and evening hours when the PBL decouples. The ES1 upslope perturbation wind is nearly 3.0 m s$^{-1}$ compared to ES2 which is less than 1.5 m s$^{-1}$ and with almost no upslope component.

Overnight, these differing wind fields are subjected to the inertial oscillation (Blackadar, 1957; Shapiro et al., 2016; Van de Wiel et al., 2010), advection, and vertical mixing associated with shear-induced turbulence. Thus, the behavior of the early morning near-surface slope flows (MS1 and MS2) and elevated jets associated with the remnant layer (MA1 and MA2) differ between IOP 1 and 2. Whereas features MS2 and MA2 appear as distinct local maxima in IOP 2, MS1 and MA1 nearly merge together. This could be due to the larger PGF at 1900 LST during IOP 1 in combination with it shifting from upslope to downslope with height (Figure 3a). This enhances vertical wind shear and shear-induced turbulence, mixing westerly momentum towards the surface overnight. Therefore, MS1 and MA1 are both westerly and blend together. During
IOP 2, however, vertical variation of the perturbation PGF is reduced (Figure 3b), and early morning atmospheric stability is increased at both the surface and within the remnant layer (Figure 4), reducing vertical mixing of momentum and enabling MS2 and MA2 to evolve independently. These processes can explain why perturbation wind MS1 is 3-5 m s\(^{-1}\) downslope while perturbation wind MS2 is 2-3 m s\(^{-1}\) upslope depending on site. MA1 and MA2 have similar magnitude (4-6 m s\(^{-1}\)) but have reduced depth during IOP 2 due to the reduced mixing. Additional work, however, is required to verify that these nocturnal processes are responsible for the observed differences in the morning wind profiles between IOPs.

When the above analysis is repeated using the HRRR analysis wind and thermodynamic fields, several differences emerge. These include the structure of the mixed-layer and perturbation winds, the diurnal variation of the PGF, and the strength of the residual layer inversion. Unlike the observational analysis, where MS1 and MA1 could be distinguished despite strong mixing, they cannot be readily identified as separate features in the HRRR analysis. Only one distinct jet maximum is apparent with a magnitude of 4-6 m s\(^{-1}\) downslope at 0500 LST during IOP 1. Additionally, the altitude of the jet maximum is 250-500 m lower than in the observational analysis (the greatest disparity is at DOW 6 in the center of the GRAINEX domain). As the HRRR analysis perturbation PGF shows good agreement with observations at 1900 LST (>2% error above 1000 m AGL and below 250 m AGL), the time of PBL decoupling, other processes are likely responsible for the anomalous behavior of the HRRR morning wind profile. The tendency for HRRR to overestimate momentum mixing, especially within the nocturnal PBL (Fovell & Gallagher, 2020) could be responsible for the single jet feature. The HRRR analysis
also shows less negative values of sensible heat flux overnight than observed, indicating the
presence of enhanced nocturnal mixing.

During IOP 2, the 0500 LST perturbation wind profile shows differences between the HRRR and
observations at all sites. While the tendency for wind to back with height is exhibited in both
observations and the HRRR analysis, wind speed and direction differ. For example, MS2 and
MA2 are underestimated by the HRRR analysis compared to observations (1.0-2.0 m s\(^{-1}\) versus
2.0-3.0 m s\(^{-1}\) for MS2 and 3.0-3.5 m s\(^{-1}\) versus 4.0-5.0 m s\(^{-1}\) for MA2; Figure 2). The
discrepancies are greatest downslope over DOW 6 and ISS 2, downslope of the irrigation.
Further, MS2 and MA2 are northeasterly and southwesterly at all sites in observations, while the
HRRR analysis shows southeasterly and northerly. At 1900, during the time of PBL decoupling,
the HRRR analysis over predicts the upslope intensity of ES2, even reversing the direction of the
wind relative to observations over ISS 2. This is contrasted with IOP 1 where the HRRR
simulated ES1 is in either fair agreement (DOW 6, ISS 2) or under estimated (ISS 3).

Comparison of the HRRR simulated fluxes to observations during IOP 2 (Supplement Figure
S2c and S2d) show that the HRRR overestimates sensible heat flux during the daytime (90 W m\(^{-2}\)
excess during peak heating) due to the lack of irrigation in the model. In fact, the observed
mean daytime Bowen ratio is 0.24 over irrigated regions during IOP 2, compared to 0.76 in the
HRRR analysis (Supplemental Table S2). Non-irrigated areas have a mean daytime Bowen ratio
of 0.39 and 0.93 in observations and the HRRR respectively. The enhanced sensible heating in
the HRRR produces greater terrain-induced baroclinicity during the daytime and evening hours
(~0.5 °C below 1000 m AGL; Supplement Figure S3c and S3d) and a correspondingly larger
PGF when the PBL decouples (-1.5E-4 m s⁻² versus -1.0E-4 m s⁻²). Further, discrepancies between the HRRR simulated and observed Tᵥ profiles are noticeably greater over the irrigated ISS 3 site than the unirrigated ISS 2 site (Figure 4), leading to an underestimation of the remnant layer capping inversion at 1900 LST. This enables greater mixing of momentum within the HRRR model, broadening MA2 compared to observations (Figure 2).

Notably, during IOP 2 ISFS observations show that irrigated regions have a mean daytime latent heat flux of 296 W m⁻² compared to 175 W m⁻² in the HRRR. Over non-irrigated regions, these values are 240 and 160 W m⁻² respectively; thus, the HRRR underestimates mean daytime latent heat flux by -121 W m⁻² over the irrigated sites but only by -74 W m⁻² at the non-irrigated locations. This is in contrast to IOP 1 where HRRR overestimated latent heat flux in both regions by 57-59 W m⁻² (Supplemental Table S3). The greater discrepancy in latent heat flux between observations and the HRRR over the irrigated region during IOP 2 suggests that irrigation contributes to the decreased sensible heat flux and enhanced latent heating seen in observations. This consequently affects lower-atmosphere Tᵥ, perturbation PGF, the Great Plains slope wind, and operational forecasting thereof.

4 Conclusions

We utilize observations collected during the GRAINEX field campaign to investigate the impacts of irrigation in upslope regions of gently sloping terrain. Our analysis shows that irrigation in upslope regions reduces terrain-induced differential heating with a corresponding weakening of the evening PGF prior to decoupling of the PBL. Comparison to HRRR analysis shows that, on average, the evening zonal component of the PGF within the PBL (below 1000 m
AGL) is overestimated by 100% when irrigation is not considered. Above the PBL, the zonal PGF is overestimated by 300% during the time of PBL decoupling. Thus, the strength of upslope flow caused by differential heating along the slope is reduced by the presence of irrigation in upslope regions. Further, irrigation observations from IOP 2 show that irrigated regions have reduced mean daytime Bowen ratio compared to non-irrigated regions with values of 0.24 and 0.39 respectively, while the operational HRRR model shows mean daytime Bowen ratios of 0.76 and 0.93 in irrigated and non-irrigated regions respectively. Thus, irrigation reduces sensible heat flux, which helps stabilize the PBL and decreases momentum exchange between near-surface wind jets and those associated with the remnant layer inversion.

Our findings are consistent with results from prior modeling studies and to the best of our knowledge are the first observational confirmation of this effect. Since the vertical profile of horizontal winds at the time of PBL decoupling evolve overnight due to inertial oscillations, vertical mixing of momentum, and differential advection, irrigation also affects near-surface and remnant layer jets. Higher stability within the nocturnal stable boundary layer over wetter soils and stronger remnant layer inversions over irrigated regions enable more independent evolution of these wind features.

Note, that while our study provides the first observational analysis of irrigation-induced boundary layer circulations, it does not allow for quantification of all relevant forcing factors. This can only be achieved through combination of observational and numerical modelling analysis. Additional analysis also needs to be conducted to investigate if the changes in PBL circulation affects cloud and precipitation formation.
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Open Research

CWSR sounding data are available via ftp at https://doi.org/10.48514/6XTH-M998. NCAR/EOL sounding data for the ISS 2 and ISS 3 sites are located at https://doi.org/10.5065/D6WH2NV0 and https://doi.org/10.26023/P0KD-873S-510V. ISFS flux data are accessible via https://doi.org/10.26023/WPSA-MFSD-MC12. HRRR analysis is available at https://doi.org/10.7278/S5JQ0Z5B. AHPS rainfall totals may be downloaded at https://water.weather.gov/precip/download.php. Data are processed using the Python programming language.

Author Contribution

R. Mahmood, U. S. Nair, E. Rappin, and R. A. Pielke Sr. coordinated GRAINEX in conjunction with other GRAINEX principal investigators. C. E. Phillips performed data collection and analysis duties. All authors were involved in the writing and editing of the manuscript.
Competing Financial Interests

The authors have no competing financial interests concerning this manuscript.
References


Figure 1: (a) The GRAINEX domain with topography shaded. Most irrigation within the study area is located west of 96.9° W (dashed line). Observation sites with rawinsondes are marked in red. ISS 2, ISS 3 and DOW 6 are circled. ISS stations are separated by ~100 km. (b) Terrain-generated slope wind circulation in non-irrigated conditions. Red line is the 850 mb pressure surface, tilted by differential heating along the slope. Black arrows indicate the resulting circulation. Latent heat flux is denoted by the blue arrow, while sensible heat flux is in red. Black ticks show height of upslope region. (c) Same as (b) but with irrigation upslope. Irrigation reduces along-slope baroclinicity, weakening the circulation, which is illustrated by the gray arrow.
Figure 2: Composited perturbation wind speed for observations (black), the HRRR (red), and the corresponding RMSE (blue). (a, b) are the wind profiles at local dawn. (c, d) are the wind profiles at local sunset. Vectors indicate direction and scale with wind speed. Wind maxima of interest are boxed and labelled.
Figure 3: Zonal component of the pressure gradient force over the GRAINEX domain as calculated from the ISS rawinsondes (solid) and the HRRR analysis (dashed). (left) Dawn and (right) sunset profiles are plotted for IOPs 1 and 2.
Figure 4: Composited virtual temperature for observations (black) and the HRRR (red) for local dawn (a, b) and local sunset (c, d).
Influence of Irrigation on Diurnal Mesoscale Circulations: Results from GRAINEX 2018

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Introduction

This supporting issue includes figures and tables that support the data analysis contained within the manuscript but are not essential for understanding the presented work. Included data are surface energy fluxes, vertical profiles of baroclinicity, vertical pressure gradient force, and near-surface pressure from GRAINEX observations and the HRRR analysis.

These data are composited across the identified clear sky days of the GRAINEX campaign to provide average conditions. Additionally, the clear sky days used in the analysis are listed in this document.

Textual sections include details of the surface flux stations deployed during GRAINEX, a surface flux argument for the lack of irrigation in the HRRR to justify its use in isolating the effects of irrigation, and a description of how the hydrostatic state of the atmosphere over the GRAINEX domain was determined.
Text S1.
Data from 10 Integrated Surface Flux System (ISFS) stations are considered in this study. While 12 stations were deployed in the GRAINEX domain, 2 were located at the boundary between the irrigated and non-irrigated cropland and assumed characteristics from both regions (Rappin et al., 2021). Thus, these 2 boundary stations are not included in the analysis. The ISFS measured 2 m temperature, pressure, and relative humidity. Additionally, wind speed and direction are measured at 10 m, and sensible and latent heat fluxes between 4 and 7 m. ISFS observations are available on 5-minute intervals.

Text S2.
In the manuscript, it is suggested that irrigation is largely lacking from the HRRR analysis due to its lack of irrigation parameterization and soil moisture observation assimilation. This is supported by analysis of surface heat fluxes in both observations and the HRRR (Supplemental Figure S2).

In ISFS observations, peak latent heat flux (LH) shows an increase from 400 to 450 W m\(^{-2}\) over irrigated sites and 300 to 350 Wm\(^{-2}\) over non-irrigated sites. Concurrently, over irrigated areas, peak sensible heat flux (SH) declines from 140 to 100 W m\(^{-2}\). Over the eastern half of the domain (non-irrigated), this decrease is from 200 to 150 W m\(^{-2}\). In HRRR analysis these trends are reversed. LH declines from 450 to 260 W m\(^{-2}\) from IOP 1 to IOP 2 over the irrigated sites and 360 to 250 over the non-irrigated sites. SH shows only a modest increase in the west, 175 to 200 W m\(^{-2}\) and remains between 200-225 W m\(^{-2}\) over the eastern, non-irrigated sites during this period. The HRRR analysis’ sharp decrease in peak LH between IOPs clearly indicates that irrigation is not present within the model.

Text S3
When determining whether the observed circulation is hydrostatic, two methods are used. First, the vertical perturbation pressure gradient force is compared to density perturbations, \(\rho'\). \(\rho'\) is computed as:

\[
\rho' = \rho - \rho_0 \quad (S1)
\]
where $\rho_0$ is the base state density and $\rho$ is the instantaneous density over ISS 3. The base state density is computed by creating daily averages from the ISS 2 rawinsonde observations.

Hydrostatic balance is then assessed according to:

$$\frac{\partial p'}{\partial z} + \rho' g = 0 \quad (S2)$$

where $p'$ is the perturbation pressure, calculated analogously to $\rho'$, $z$ is height, and $g$ is gravity.

Figure S4 shows the average 1500 LST vertical $\rho' g$ and pressure gradient profiles and demonstrates that the atmosphere is in hydrostatic balance. This holds true for all rawinsonde launch times. Similar results are also found using the HRRR analysis.

Second, to compute the non-hydrostatic pressure change across the GRAINEX domain, the hydrostatic pressure decrease due to elevation is subtracted from the observed decrease in surface pressure between ISS 2 (east) and ISS 3 (west):

$$\Delta P_{NH} = (P_{ISS3} - P_{ISS2}) - P_{ISS2} \cdot \exp \left( -\frac{g \Delta z}{R_d \bar{T}_v} \right) \quad (S3)$$

where $p$ is pressure, $g$ is gravity, $\Delta z$ is the elevation change, $R_d$ is the dry air gas constant, and $\bar{T}_v$ is the pressure-weighted mean virtual temperature between the stations. Average time series of the total and non-hydrostatic pressure changes (Figure S5) show that the non-hydrostatic pressure change is nearly two orders of magnitude less than the observed change. Additionally, the computed non-hydrostatic pressure change is on the order of instrument error. Thus, it is concluded that the atmosphere over the GRAINEX domain is predominantly hydrostatic.
Figures

Figure S1. Mean diurnal curves of down-welling solar radiation from ISFS and the HRRR analysis with nighttime shaded. Means are computed by averaging the stations in each region first and then compositing the resulting time series. ISFS data are smoothed using a 30 minute rolling average. The HRRR data are hourly.
Figure S2. Mean near-surface sensible (SH) and latent heat (LH) fluxes measured by the Integrated Surface Flux System (ISFS) stations and HRRR analysis for IOP 1 and IOP 2. Sensible heat flux is in red, and latent heat flux is in blue. Shading indicates nighttime. ISFS data are smoothed using a 30 minute rolling average. The HRRR data are hourly.
Figure S3. Mean difference in virtual temperature between ISS 2 and ISS 3 (ISS 2 minus ISS 3) from observations (a, c) and the HRRR analysis (b, d).
Figure S4. Mean vertical profiles of perturbation density (solid) and perturbation vertical pressure gradient (dashed) for IOPs 1 (left) and 2 (right) at 1500 LST (2100 UTC). The vertical force balance is in blue. Vertical pressure gradient has a 120 (10 pts) meter sliding average applied for smoothing.
Figure S5. Mean time series of the observed (black), hydrostatic (red), and non-hydrostatic (blue) pressure change between the western (ISS 3) and eastern (ISS 2) sites for IOPs 1 (bottom) and 2 (top).
Tables

**Table S1.** Selected clear days during the GRAINEX campaign. Days were selected using a combination of GOES-16 visual satellite imagery and surface flux analysis.

<table>
<thead>
<tr>
<th>IOP 1</th>
<th>IOP 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 May 2018</td>
<td>19 July 2018</td>
</tr>
<tr>
<td>2 June 2018</td>
<td>21 July 2018</td>
</tr>
<tr>
<td>3 June 2018</td>
<td>22 July 2018</td>
</tr>
<tr>
<td>5 June 2018</td>
<td>24 July 2018</td>
</tr>
<tr>
<td>10 June 2018</td>
<td></td>
</tr>
</tbody>
</table>

**Table S2.** Mean daytime Bowen Ratio from ISFS observations and HRRR analysis for IOPs 1 and 2 over irrigated and non-irrigated regions.

<table>
<thead>
<tr>
<th>IOP 1</th>
<th>Irrigated</th>
<th>Non-irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISFS</td>
<td>0.39</td>
<td>0.58</td>
</tr>
<tr>
<td>HRRR</td>
<td>0.42</td>
<td>0.77</td>
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<table>
<thead>
<tr>
<th>IOP 2</th>
<th>Irrigated</th>
<th>Non-irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISFS</td>
<td>0.24</td>
<td>0.39</td>
</tr>
<tr>
<td>HRRR</td>
<td>0.76</td>
<td>0.93</td>
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</table>

**Table S3.** Mean daytime Latent Heat Flux from ISFS observations and HRRR analysis for IOPs 1 and 2 over irrigated and non-irrigated regions.

<table>
<thead>
<tr>
<th>IOP 1</th>
<th>Irrigated (W m⁻²)</th>
<th>Non-irrigated (W m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISFS</td>
<td>276.62</td>
<td>217.90</td>
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<tr>
<td>HRRR</td>
<td>335.28</td>
<td>274.83</td>
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</table>

<table>
<thead>
<tr>
<th>IOP 2</th>
<th>Irrigated</th>
<th>Non-irrigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISFS</td>
<td>296.21</td>
<td>240.23</td>
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<tr>
<td>HRRR</td>
<td>175.07</td>
<td>166.43</td>
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</table>