Irrigation in the Texas High Plains was developed solely from the Ogallala (High Plains) Aquifer, as precipitation and surface water resources in the region are generally inadequate for this purpose. The Ogallala aquifer is one of the largest freshwater aquifers in the world; however it is a closed system. Consequently, withdrawals have greatly exceeded recharge, resulting in severe declines in ground water levels since irrigation development began. Declining well yields, changing water quality and increasing pumping energy costs continue to affect withdrawal rates, and therefore, crop productivity. If the present trend continues, the long-term economic viability of irrigated agriculture in the Texas High Plains will be adversely affected. One impediment to better ground water management is that the overall water balance of the region is still not fully understood, particularly in terms of evapotranspiration (ET), recharge and precipitation as they vary spatially in the region.

ET has long been recognized as the process that plays the most important role in determining exchanges of energy and water mass between the hydrosphere, atmosphere and biosphere (Sellers et al., 1996). In agriculture, it is a major consumptive use of irrigation water and precipitation on agricultural land. Any attempt to improve water use efficiency must be based on reliable estimates of ET, which includes water evaporation from land, vegetative and water surfaces and transpiration by vegetation. ET varies regionally and seasonally according to weather and wind conditions (Hanson, 1991). Understanding these variations in ET is essential for managers responsible for planning and management of water resources especially in arid and semi-arid regions of the world where crop water demand generally exceeds precipitation and requires irrigation from surface and/or groundwater resources to meet the deficit.

Remote sensing based land surface energy balance models are better suited for estimating crop water use at a regional scale (Allen et al., 2007a). Numerous remote sensing algorithms are available for estimating the magnitude and trends in regional evapotranspiration. Three models: Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 2005), Mapping Evapotranspiration with Internalized Calibration (METRIC™; Allen et al., 2007b), and Two Source Energy Balance (TSEB; Kustas and Norman, 1999) are most commonly used. These models convert satellite sensed radiances into land surface characteristics such as albedo, leaf area index, vegetation indices, surface thermal emissivity and surface radiometric temperature to estimate LE (latent heat flux, W m⁻²) or ET (e.g., mm d⁻¹) as a “residual” of the land surface energy balance equation \[ \text{ET} = (R_n - G - H)/\lambda_v \], where \( R_n \) is net radiation, \( G \) is soil heat flux, \( H \) is sensible heat flux (all in W m⁻² units), and \( \lambda_v \) is latent heat of vaporization (≈2.45 M J kg⁻¹). To validate such remote sensing based estimates of regional ET, ground-truth can be obtained from lysimetric measurements and other relatively small areal LE determinations (with Scintillometer, Eddy Covariance or Bowen Ratio systems).

Surface temperature is one of the key boundary conditions in most energy balance models for estimating spatially distributed ET. Numerous remote sensing satellites provide thermal images that can be used to derive radiometric surface temperature. However, the spatial resolution of these thermal (Continued on page 6)
images is coarser than that acquired in other wavelengths such as visible, NIR (Near Infrared) and SWIR (Shortwave-Infrared). For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor provides thermal images at 1000-m resolution compared to 250-m resolution for images acquired in other bandwidths on the same satellite platform. Further, time intervals between successive satellite overpasses (repeat cycle) over the same geographic area vary from satellite to satellite. The more frequent the repeat coverage, the coarser the spatial resolution of the images acquired. For example, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor has a repeat cycle of 8 days with 15-90 m spatial resolution compared to daily coverage of MODIS with 250-1000 m resolution.

In the Texas High Plains, high resolution daily ET maps would help in scheduling irrigation. ET maps derived from satellites with daily coverage such as MODIS, Advanced Very High Resolution Radiometer (AVHRR), and Geostationary Environmental Satellite (GOES) would not satisfy producer needs because their pixel size is larger than individual fields in the region, causing significant errors in distributed ET estimation (Tasumi et al., 2006). The errors in estimated ET will be partly due to the presence of contaminated pixels, i.e., pixels with multiple land uses/vegetation types with significant differences in cover, surface roughness and/or moisture content (Kustas et al., 2004). This condition is more common in arid and semi-arid regions where fully irrigated fields are usually surrounded by extremely dry landscape. Limited research has been done to evaluate the scale influences on the estimation of ET using multiple aircraft and satellite sensors (McCabe and Wood, 2006 and Kustas et al., 2004 in humid Iowa region; Jacob et al., 2002 for Mediterranean climate). However, no such study has been implemented with both aircraft and satellite sensor platforms in semi-arid or arid regions of the U.S. to evaluate scale influences on estimating ET using land surface energy balance models. Moreover, previous studies assessed scale effects by comparing ET estimates against surface fluxes derived from eddy covariance systems. It is known that the eddy covariance method has an energy balance closure problem i.e., \( R_{ec} ≠ H + LE + G \) (Oncley et al., 2000). Therefore, calibration of the EB models against lysimetric and/or well-calibrated scintillometer measurements over irrigated and dryland conditions may enhance their ability to estimate regional ET accurately. Detailed discussion on the present status and challenges in ET mapping for agricultural management can be found in Gowda et al. (2007).

Given these knowledge gaps in ET remote sensing research, there is a need for thorough evaluation of existing and new remote sensing based ET models as well as flux measurement systems such as scintillometers, Bowen Ratio (BR) and Eddy Covariance (EC) systems for the semi-arid Texas High Plains using lysimeter data. In addition, opportunity exists to utilize simultaneously acquired high resolution visible, NIR and SWIR images from MODIS and thermal images from other high resolution sensors such as Landsat TM to improve the frequency and resolution of ET maps, making them useful for crop irrigation scheduling and general landscape hydrologic balance.

**BEAREX07**

BEAREX07 is a multi-agency/university collaborative research effort between the Conservation and Production Research Laboratory (CPRL), USDA-ARS; University of Texas – Austin, TX; Utah State University, Logan, UT; and Arid-Land Agricultural Research Center (ALARC)-USDA-ARS, Maricopa, AZ. The main objectives of this research effort are to evaluate: (1) land surface energy balance and crop coefficient-based ET models for their ability to estimate ET at point, plot, field, landscape and regional scales; (2) the effects of remote sensing pixel resolution (thermal band) on modeled energy balance components of irrigated and dryland cropping systems and rangeland systems; (3) existing and new algorithms to improve spatial resolution of surface temperature data derived from Aircraft/Landsat/ASTER/MODIS thermal images using high resolution visible, NIR and SWIR images; (4) Large Aperture Scintillometer (LAS) systems for their ability to estimate path-weighted sensible heat fluxes over heterogeneous landscapes; and (5) BR and EC systems for their ability to estimate sensible and latent heat fluxes in the semi-arid, highly advective Texas High Plains.

BEAREX07 was conducted during the 2007 cropping season in and around the CPRL- USDA-ARS site, Bushland, TX (Fig. 1). The CPRL is the home of four large monolithic weighing lysimeters (3 m length x 3 m width x 2.4 m depth) located in the middle of 4.7-ha (210 x 225 m) fields that are larger than Landsat TM’s thermal pixel size (120 x 120 m). In 2007, two of the lysimeters (SW and NW) were planted to dryland grain sorghum in clumps as part of another study (Fig. 1). The SE and NE lysimeter fields were planted to forage corn and sorghum, respectively, and were irrigated. One small lysimeter (1.5 m by 1.5 m by 2.4 m deep) is located in the grass reference ET weather station field (0.31 ha) which is a part of the Texas High Plains ET Network (TXHPET, 2006). Each lysimeter field is equipped with one net radiometer [QRST, Radiation and Energy Balance Systems (REBS)], Seattle, WA and one infrared thermometer (IRT) (2G-T-80F/27C, Exergen, Watertown, MA) and three soil heat flux plates (Campbell Scientific Inc., Logan, UT) for measuring net radiation, surface temperature, and soil heat fluxes, respectively.

(See Figure 1 on following page for Location of study area)

BEAREX07 consisted of six remote sensing campaigns for acquiring high resolution aircraft imagery, which were scheduled to coincide with ASTER and Landsat TM overpasses. The Utah State University (USU) airborne multispectral digital system was used to acquire high-resolution short wave (green, red and near-infrared) and thermal infrared imagery. More information on this sensor can be found in Neale and Crowther (Continued on page 7)
The spatial resolution of acquired images was 0.5 m in the shortwave bands and 1.8 m in the thermal infrared band. The flight lines were planned to ensure 30% overlap between parallel flight lines and to guarantee complete coverage over the study area. In addition to aircraft images, a research plan was submitted to the ASTER Science Team, National Aeronautical and Space Administration in collaboration with Dr. Andrew French, ALARC-USDA-ARS, and it was approved for acquisition of ASTER images during the BEAREX07.

During the 2007 planting season, three LAS were deployed at the CPRL in collaboration with Dr. Bridget Scanlon, University of Texas - Austin: one across two dryland lysimeter fields on the west side, one across two irrigated lysimeter fields on the east side, and one over rangeland (Fig. 1). The orientation of each LAS was selected to have the scintillometer’s path perpendicular to the predominant wind direction and to avoid direct sun light on the lenses. Refractive index of air measurements was made on a continuous time scale at 1 Hz and averaged at 15-min intervals, synchronized with the weather station and lysimeter measurement averaging period. In addition, infra-red thermometers, net radiometers and soil heat flux plates were installed near both transmitter and receiver to measure surface temperature, net radiation and soil heat flux over 15-min intervals. The height of each LAS was adjusted to maintain its height above the crop surface throughout the BEAREX07 campaign. For estimating sensible heat flux (H) from the refractive index of air, air temperature and wind speed data are required. A weather station was installed on the rangeland to complement the LAS system and to augment the existing weather station data in the study area.

Field data collected during the remote sensing campaigns included leaf area index, wet/dry biomass, crop height, leaf width, crop yield in addition to row direction and width and plant density in 40 locations, thus capturing the crop variability/management practices within the CPRL. Soil moisture content was determined using soil water reflectometers (model CS616, Logan, UT) and Time Domain Reflectometry (TDR). Surface reflectance and surface temperature measurements at the time of aircraft/satellite overpasses were made using a hand-held multispectral radiometer/scanner (MSR5; CROPSCAN, Inc., Rochester, MN) and a variable zoom IRT Agri-Therm II (Everest Inter- science Inc.), respectively. In addition, soil water moisture content and continuous surface temperature data were available at several different locations as part of numerous ongoing experiments at the CPRL. Ground truth data for regional land use mapping were collected in a six-county area around the CPRL.

CURRENT STATUS
A comprehensive ground truth database was developed for evaluating remote sensing based ET models. During the BEAREX07 campaign, 25 high resolution aircraft images were acquired through the cropping season. Seven Landsat TM images that were acquired during BEAREX07 were purchased from the U.S. Geological Survey and were cloud free for most part of the scenes including the CPRL. Unfortunately, NASA did not acquire the requested ASTER images for unknown reasons. MODIS data acquired during the BEAREX07 were downloaded.
from the MODIS website. Continuous measurements were made with the LAS systems throughout the 2007 cropping season.

At present, we are geometrically/radiometrically correcting the high resolution aircraft imagery for lens radial distortions and geo-rectifying using common control points to an ortho-photograph base map. The rectified images will be stitched along the flight lines forming image strips. The short wave imagery will be calibrated in terms of reflectance using the system calibration and measurements of incoming solar irradiance measured with an Exotech radiometer placed over a standard reflectance panel with known bi-directional properties, set out at the CPRL at the time of aircraft overpasses. The image strips will be corrected for atmospheric effects using the MODTRAN radiative transfer model. The strips will then be stitched together forming a mosaic covering the entire study area with pixels representing at-surface reflectance. The thermal imagery will be processed in a similar way. The individual thermal images corrected for lens radial distortions will be rectified to the 3-band multispectral mosaic and stitched together into larger image strips along portions of the flight lines. These strips will be combined in a mosaic together to cover image blocks. These rectified image blocks will eventually be combined to form a large thermal mosaic covering the entire study area. The image mosaic will be calibrated first to obtain at-sensor apparent temperatures using the sensor calibration bar at the bottom of each image and then calibrated for atmospheric interference and surface thermal emissivity using MODTRAN (radiative transfer software). Efforts are also being made to process Landsat 5 TM images for evaluating ET models such as METRIC, SEBAL, TSEB, Surface Aerodynamic Temperature (SAT; Chávez et al., 2005) and Simplified Surface Energy Balance (SSEB; Senay et al., 2007).

BEAREX08
BEAREX07 was successfully completed. We are now planning the BEAREX08 campaign with cotton on our irrigated and dryland lysimeter fields during the 2008 cropping season. We are expecting Dr. Michael Salvage, a visiting scientist from South Africa, to join us to work on the energy balance closure problem with EC systems. Also, efforts are being made to broaden the scope of the BEAREX08 in collaboration with two other USDA-ARS laboratories: the Hydrology and Remote Sensing Laboratory, Beltsville, MD and the Arid Lands Agricultural Research Center, Maricopa, Arizona.

EXPECTED RESULTS
This research is the most comprehensive remote sensing ET modeling study at point, plot, field, landscape and regional scales in the Texas High Plains. It provides quality assured datasets for evaluating/improving existing remote sensing based ET models and developing new models if required. It is also expected to provide an operational ET remote sensing methodology for high resolution regional ET mapping for the Texas High Plains.

References