Understanding of crop phenology using satellite-based retrievals and climate factors – a case study on spring maize in Northeast China plain

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Abstract. Land surface phenology is an efficient bio-indicator for monitoring terrestrial ecosystem variation in response to climate change. Numerous studies point out climate change plays an important role in modulating vegetation phenological events, especially in agriculture. In turn, surface changes caused by geo-biological processes can affect climate transition regionally and perhaps globally, as concluded by Intergovernmental Panel on Climate Change (IPCC) in 2001. Large amounts of research concluded that crops, as one of the most sensitive bio-indicators for climate change, can be strongly influenced by local weather such as temperature, moisture and radiation. Thus, investigating the details of weather impact and the feedback from crops can help improve our understanding of the interaction between crops and climate change at satellite scale. Our efforts start from this point, via case studies over the famous agriculture region in the Northeast China’s plain to examine the response of spring maize under temperature and moisture stress. MODIS-based daily green vegetation information together with frequent field specification of the surface phenology as well as continuous measurements of the routine climatic factors during seven years (2003-2009) is used in this paper. Despite the obvious difference in scale between satellite estimations and field observations, the inter- and intra-annual variation of maize in seven-years’ growth was captured successfully over three typical spring maize regions (Fuyu, Changling, and Hailun) in Northeast China. The results demonstrate that weather conditions such as changes of temperature and moisture stress provide considerable contribution to the year-to-year variations in the timing of spring maize phenological events.

1. Introduction
The interaction between vegetation and climate involves the effect of climate changes on the vegetation development, and contribution of vegetation to modulate the climatic factors. Land surface phenology, defined as the seasonal pattern of variation in the vegetated land surfaces[1], is an efficient bio-indicator for monitoring the variation of land surface vegetation in response to changes in climatic factors. The timing of leaf development in many temperate deciduous species correlates with the cumulative springtime temperature [2-3]. The length of growing season may strongly affect the associated seasonality of ecosystem-scale carbon exchange especially in deciduous forests [4]. Conversely, numerous studies show that vegetation phenology can be influenced by local climate changes. Temperature is the main factor controlling the seasonality of vegetation growth in humid temperate climates [5-6], while water availability governs vegetation phenology in arid and semiarid ecosystems, and in seasonally dry tropical climates [7] where rainfall activates the emergence of green leaves and controls the duration of vegetation growth [8]. The pattern of precipitation during the rainy season is critical to crop germination, growth, and harvest [9]. The early or late arrival of precipitation events can affect estimations of agriculture growth and yield. In addition, changes in vegetation phenology can also affect the surface water and energy balance. Considerable land surface phenology...
investigations have been devoted to the development of methods for identifying and calculating phenological features using time series of vegetation indices [10-12].

In this study, daily MODIS 500m NBAR-based phenological markers are compared to ground measurements carried out over three homogenous spring maize sites. More precisely, the primary objective is to explore the potential of MODIS NBAR generated by MODIS direct broadcast system, to characterize the growth trajectories of multiple year maize phenology events. A secondary objective is to improve our understanding on the effect of weather stress on crop growth over the investigated spring maize regions.

2. Data and Method

The ground-based maize growth stages were routinely collected over three typical agro-meteorological stations in the famous agriculture region of the Northeast China’s plain. These stations, respectively located in Fuyu, Changling, and Hailun counties (Figure 1), have been sowed with spring maize over more than 90% of the area for tens of years. The in situ dataset used in this case study includes frequent field specification of the surface phenology information and varieties for each maize growth period during 2003-2009. Table 1 summarized the ground observations of major growth stages available in the historic dataset for the above three stations. According to the field criterion defined by Chinese Meteorological Administration [13], the date recorded for each growth stage is the “timing” when ~50% of the individual crops have entered into the growth phase.

Table 1. The major growth stages and varieties of spring maize collected at sites Fuyu, Changling, and Hailun during 2003-2009

| Site   | Year | Variety | VE   | V 12  | VT   | Milking | Physiological maturity |
|--------|------|---------|------|-------|------|---------|------------------------|
| Fuyu   | 2003 | Longdan13 | 5/18 | 7/12  | 8/04 | 9/12    | 10/08                 |
|       | 2004 | Longdan13 | 5/22 | 7/04  | 7/26 | 9/04    | 9/28                  |
|       | 2005 | Nengdan3  | 5/28 | 7/10  | 7/27 | 9/02    | 9/26                  |
|       | 2006 | Suiyu3     | 5/22 | 7/08  | 8/01 | 9/10    | 9/28                  |
|       | 2007 | Suiyu3     | 5/22 | 7/06  | 7/26 | 9/02    | 9/26                  |
|       | 2008 | Qishan355  | 5/20 | 7/04  | 7/26 | 9/06    | 9/22                  |
|       | 2009 | Qishan355  | 5/22 | 7/20  | 8/06 | 9/12    | 10/02                 |
| Changling | 2003 | Simi21     | 5/18 | 7/08  | 7/27 | 8/28    | 9/20                  |
|       | 2004 | Jidan158   | 5/16 | 7/14  | 7/31 | 9/10    | 9/28                  |
|       | 2005 | Tie12      | 5/14 | 7/16  | 7/27 | 8/28    | 9/20                  |
|       | 2006 | Xinchun28   | 5/22 | 7/10  | 8/04 | 8/28    | 9/28                  |
|       | 2007 | Zhendan958  | 5/22 | 7/18  | 8/06 | 9/08    | 9/30                  |
|       | 2008 | N/A        | 5/20 | 7/08  | 7/25 | 8/22    | 9/18                  |
|       | 2009 | PingAn86   | 5/08 | 7/16  | 7/29 | 8/24    | 9/20                  |
| Hailun | 2003 | Haiyu6     | 5/26 | 7/08  | 7/24 | 8/26    | 10/08                 |
|       | 2004 | Haiyu6     | 5/24 | 7/08  | 7/28 | 8/28    | 9/26                  |
|       | 2005 | Haiyu6     | 5/24 | 7/06  | 7/21 | 8/26    | 9/28                  |
|       | 2006 | Haiyu6     | 5/22 | 7/06  | 7/21 | 8/28    | 9/28                  |
|       | 2007 | Haiyu6     | 5/24 | 7/08  | 7/22 | 8/26    | 9/28                  |
|       | 2008 | Haiyu6     | 5/24 | 7/08  | 7/19 | 8/26    | 9/28                  |
|       | 2009 | Haiyu6     | 5/24 | 7/14  | 8/02 | 8/30    | 10/02                 |

Note: VE-vegetation emergence; V12-vegetation 12 leaves visible; VT-vegetation tassel.
In addition, daily measurements of 50-year (1961-2010) historical climate for this region, which were systematically collected by the Chinese climate observation network, were processed for each site. For sites Fuyu, Changling and Hailun, the annual mean temperatures are 2.84°C, 5.67°C, and 2.12°C respectively, and their related annual mean precipitation are 436.5mm, 430.5mm, and 547.9mm from 1961 to 2010. In 2000s, several studies indicate that Fuyu, Changling, and Hailun site respectively belong to mid-late, late, and medium maturity region, based on the annual ≥10°C accumulated temperature [14]. Monthly averaged “accumulated ≥10°C active temperature” (Tacc10) from May to September (DOY 120-290), and monthly precipitation for each year, were computed to determine the anomalies (departures from normal) for the whole growing season, and to investigate the inter-annual variation of low-temperature and precipitation stress. According to the historical data, the first frost day for all three sites is later than the physiological maturity stage during 2003-2009, which removed the risk of frost damage from our investigation, as well as the less deficit of radiative flux in terms of 50-years record of the ground data.

A time series of daily MODIS spectral NBAR (BRDF-adjusted reflectance) at local solar noon (LSN) were generated for each site in each growth period (DOY 120-290) during 2003-2009, through the MODIS direct broadcast albedo/BRDF system developed with a weight strategy in terms of the age and quality of the daily rolling observations [15] utilizing the semi-empirical kernel-driven RossThickLiSparse-Reciprocal (RTLSR) model [16], and officially released via University of Wisconsin-Madison Space Science and Engineering Center [17]. Satellite-based vegetation indices, which provide an indication of the canopy greenness and wetness, have been commonly used to monitor seasonal, inter-annual, and long-term variations of vegetation structural, phenological and biophysical parameters [18]. Vegetation indices (spectral transformations of two or more bands) enhance the contribution of vegetation properties and allow reliable spatial and temporal inter-comparisons of vegetation activities and the Enhanced Vegetation Index (EVI) and Normalized Difference Water Index (NDWI), which are most widely used in vegetation studies [19-20]. As the values of EVI and NDWI vary with sun and view geometry [21] on the order of 0.05-0.20 [22], it is desirable to use view-angle-corrected reflectance such as NBAR for consistent comparisons. Therefore, time series of EVI and NDWI (calculated from MODIS band 7, thus named as NDII7) for each study site were calculated from the resultant MODIS 500m NBARs for each day in the growth period of maize (day 120 to 290) of year 2003-2009. This study utilized a rolling 16-day strategy with an emphasis on the most recent and high quality observation in the dynamic input stream by dropping the oldest and adding the newest looks [15] to retrieve BRDFs, spectral albedo quantities from high-quality, multi-spectral, cloud-free, atmospherically-corrected surface reflectance. To remove directional effect from view geometry, nadir BRDF-adjusted reflectance (NBAR) data were also generated for the solar zenith angle of local solar noon of the most recent day of the retrieval period.

Figure 2. Daily MODIS-NBAR derived EVI (upper left, X: DOY; Y:EVI), NDWI (Upper right, X:DOY; Y:NDWI), and monthly ≥10°C accumulated active temperature (orange) and precipitation (blue) in the right Y-axis, with daily EVI (green) in the left Y-axis of the lower panel for Fuyu during DOY 120-290 of year 2003-2009
3. Result and Discussion
In this part, variation of green vegetation amount and vegetation water content during DOY 120-290, when is spring maize growth period, from year 2003 to 2009 was investigated. Figures 2-4 present the dynamics of EVI and NDII7 along with the historic monthly precipitation and Tacc10, over the entire study period respectively for sites Fuyu, Changling, and Hailun. Footprints of phenological evolution through the daily 500m direct broadcast MODIS NBAR-derived EVI and NDII7 for the three sites exhibit similar time-series of inter- and intra-annual patterns. In all cases, it can be easily observed that EVI and NDII7 increase and reach the maximum values from early May to late July (DOY 120-200 or so), and then decreases from late July to early October (DOY ~200-290) with various dynamic ranges. Compared with the field-based record of growth stages (Table 1), both the MODIS daily direct broadcast NBAR-based EVI and NDII7 capture the main growth features of the spring maize with a rapid green-up in June (DOY 160-180), followed by a slower increase after 7-9 leaves with collars visible (V7-9). Then, most indices plots reach their highest value after several days further development before entering into the tasseling stage, with a gradual decrease during the tasseling and flowering stages, and a final speeding-up drop to the harvest season in late September. The daily NBAR based vegetation indices in Figures 2 -4 do capture some fine details during the periods of rapid change in the growing season. For instance, in the flowering and ripening periods, which are captured with a large number of high quality full retrievals, the daily EVI plots exhibit a really shallow bowl-shape, particularly in the NBAR-EVI plot. In general, the tassels and silks are light yellow, which partly decreases the “greenness” of the crop, reduces the reflectance of NIR band, and induces the slight decrease of the EVI. When the flowering period is completely over, the EVI values sometimes rebound slightly then drop with an elevated speed.

In order to gain a better understanding of the intrinsic reason induced phenology changes of these spring maize, the monthly accumulated ≥10°C active temperature (Tacc10) and monthly precipitation were also presented in figures 2-4, as well as the departures of growth duration, accumulated ≥10°C active temperature, and precipitation for each maize growth period (in table 2). Beside the variety and management practices, the main environmental factors influencing maize growth are temperature and moisture for this agriculture region. Figures 2-4 clearly display the temporal changes of MODIS
NBAR-derived EVI and NDII7 over three sites, span the whole period from sowing to physiological maturity (DOY 120-290). A good distribution of precipitation and temperature is close to optimal requirements for each growth stage, such as 2005 and 2008 of Hailun, provides an increasing chance of good maize growth and potential high production yield. Compared with other years for site Fuyu, EVI peak values have reduced in 2003, 2006 and 2009, and greennup delayed in 2003 and 2009. Numerous studies indicate water stress during vegetative growth stages (from sowing to V12) will reduce stem and leaf cell expansion as well as dry matter accumulation, and then result in reduced crop height and leaf area. Thus, the lack of precipitation in May of 2003, 2006 and 2009 caused moisture stress, may be the major reason limited the plant growth during early vegetative stages. While in the reproductive stages, especially during pollination and grain-filling, severe moisture stress can result in delayed silking and reduced pollination due to lack of viable pollen and reduced synchronization between silking and pollination. Under severe stress, some plants will not form any silks, or cause a late emergence of silks after pollen production, which is similar to what happened in year 2006 and 2009 of site Changling. Considering various maize varieties sowed at Fuyu and Changling, Hailun sowing with the identical variety “Haier6” around May 8th during 2003-2009 is a better place to discern the inter-annual phenology changes induced by the variation of weather condition on agriculture. EVI plots of year 2009 for Hailun has a slow and two-weeks-delayed climbing up to its reduced peak value. Although table 2 indicates in 2009, the historical climate records show a 204.50mm precipitation and 34.88°C·day accumulated ≥10°C active Tacc10 above 10-years average, an abnormal distribution with no more than 10mm precipitation in May and over 300mm in June may cause the moisture stress on leaves development during early vegetative growth periods.

### Table 2. Departures of growth duration, accumulated ≥10°C active temperature, and precipitation from the 11-years average (2000-2011) during 2003-2009, stratified by 3 phenological periods for site Fuyu, Changling, and Hailun.

| Site   | Year | diff. of growth duration | diff. of ≥10°C Tacc10 | diff. of Precipitation |
|--------|------|--------------------------|------------------------|------------------------|
|        |      | (day)                    | (°C·day)               | (mm)                   |
|        | VP   | RP                       | WGP                    | VP                     |
|        |      |                          | WGP                    |                        |
| Fuyu   | 2003 | 8.60                     | 0.00                   | 13.60                  | 59.80                  | -137.95               | -78.15               | 50.37                  | -24.17               | 26.20                  |
|        | 2004 | -0.40                    | 4.00                   | 3.60                   | 19.70                  | 14.65                 | 34.35                | -146.13                | 34.83                | -111.30               |
|        | 2005 | -8.40                    | 1.00                   | -7.40                  | -106.50                | 26.05                 | -80.45               | 50.37                  | -24.17               | 26.20                  |
|        | 2006 | -1.40                    | -2.00                  | -3.40                  | -25.60                 | -24.05                | -49.65               | 132.07                 | -7.17                | 124.90                 |
|        | 2007 | -2.40                    | 2.00                   | -0.40                  | -32.70                 | 130.85                | 98.15                | -88.33                 | -52.47               | -140.80               |
|        | 2008 | -2.40                    | -2.00                  | -4.40                  | -25.60                 | 50.45                 | 24.85                | 5.17                   | -72.17               | -67.00                 |
|        | 2009 | 8.60                     | -3.00                  | 5.60                   | -10.80                 | -121.15               | 139.75               | 203.67                 | 22.93                | 226.60                 |
| ChangLing | 2003 | -2.10                    | -1.40                  | -3.50                  | -76.59                 | -42.18                | -118.77              | 87.18                  | 19.20                | 106.38                 |
|        | 2004 | 6.90                     | 2.60                   | 9.50                   | 49.31                  | -34.78                | 14.53                | 29.58                  | -10.50               | 19.08                  |
|        | 2005 | 4.90                     | -1.40                  | 3.50                   | -59.89                 | -8.08                 | -67.97               | 58.68                  | 46.10                | 104.78                 |
|        | 2006 | 0.90                     | -1.40                  | -0.50                  | 48.11                  | -66.38                | -18.27               | -45.22                 | -4.00                | -49.22                 |
|        | 2007 | 3.90                     | -1.40                  | 2.50                   | 149.21                 | -38.88                | 110.33               | 7.08                   | -39.70               | -32.62                 |
|        | 2008 | -7.10                    | -1.40                  | -8.50                  | -115.09                | 17.92                 | -97.17               | -10.02                 | 27.80                | 17.78                  |
|        | 2009 | 3.90                     | -3.40                  | 0.50                   | -12.09                 | 5.52                  | -6.57                | -17.02                 | -79.70               | -96.72                 |
| Hailun  | 2003 | 6.40                     | 9.10                   | 15.50                  | 3.28                   | -78.66                | -75.38               | -51.60                 | 208.76               | 157.16                 |
|        | 2004 | 3.40                     | -6.90                  | -3.50                  | 100.28                 | -69.86                | 30.42                | -121.40                | -42.94               | -164.34                |
|        | 2005 | -1.60                    | 2.10                   | 0.50                   | -60.92                 | 10.74                 | -50.18               | -29.80                 | 63.76                | 33.96                  |
|        | 2006 | -1.60                    | 2.10                   | 0.50                   | -25.92                 | 2.54                  | -23.38               | 69.30                  | 32.06                | 101.36                 |
|        | 2007 | -0.60                    | 1.10                   | 0.50                   | 6.98                   | 53.74                 | 60.72                | -10.40                 | -65.04               | -75.44                 |
|        | 2008 | -3.60                    | 4.10                   | 0.50                   | -25.62                 | 64.14                 | 38.52                | 64.50                  | -5.74                | 58.76                  |
|        | 2009 | 12.40                    | -5.90                  | 6.50                   | 34.88                  | -138.56               | -103.68              | 204.50                 | -91.44               | 113.06                 |

Note: Vegetative Period (VP) from sowing to start of reproductive stage; Reproductive Period (RP) for grain-filling; and the Whole Growth Period (WGP) from sowing to physiological maturity.

### 4. Summary

This study investigated the nature variation of spring maize phenological events, for the first time, by a new developed daily MODIS 500m reflectance anisotropy product. The daily MODIS 500m
reflectance anisotropy products were employed to retrieve daily EVI and NDWI for typical spring maize regions in Northeast China. Field-based phenological measurements including frequent field specification of surface phenology information, subjective estimation from numerous local observers, were acquired respectively from above three study sites. Compared with the ground records over the extended region, these EVI and NDWI trajectories derived from the daily MODIS NBAR products captured not only the detailed footprint and principal attributes of the phenological events (such as tasseling and silking) but also the substantial inter-annual variability induced by weather conditions (temperature and moisture stresses). In this research, a link between traditional ground-based measurements and satellite-based retrievals is investigated to explore details of phenological phase. Ground data can improve our understanding on the biological life-cycle events of spring maize. Note that land surface phenology is a concept over the pixel scale with mixed biomes components, while the ground measures for special vegetation species often record the emergence of phenology events. Thus, further efforts are needed to determine the percentage of individual phenological events or the time when a phenological event dominates the signal in a pixel. In addition, the possible presence of residual aerosol, cloud contamination, or snow may induce variation to the detection.

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Reference
[1] Jolly W M, Nemani R, and Running S W 2005 Global Change Biology. 11 619-632
[2] Cannell M G R, and Smith R I 1983 Journal of Applied Ecology 20 951-963
[3] Zhang X, Goldberg M D, Yu Y 2012 Agricultural and Forest Meteorology. 158 21-29
[4] Richardson A D, Jenkins J P, Brasswell B H, Hollinger D Y, Ollinger S V, Smith M-L 2007 Ecosystem ecology. 152 323-334
[5] Schwartz M D 1998 Nature 394(6696) 839-840
[6] Zhang X, Friedl M A, Schaaf C B, and Strahler A H 2004 Global Change Biology 10 1133-1145
[7] Kramer K, Leinonen I, and Loustau D 2000 International Journal of Biometeorology 44 67-75
[8] Cook G D, and Heerdeneg R G 2001 International Journal of Climatology 21 1723-1732
[9] Lobell D B, and Field C B 2007 Environmental Research letters doi: 10.1088/1748-9326/2/1/ 014002
[10] Schwartz M D, Reed B C, and White M A 2002 International Journal of Climatology 22 1793-1805
[11] Tan B, Morisette J T, Wolfe R E, Gao F, Ederer G A, Nightingale J, Pedelty J A 2011 IEEE Journal of Selected Topics in Applied Earthobservations and Remote sensing 4(2) 361-371
[12] Zhang X, Friedl M A, Schaaf C B, Strahler A H, Hodges J C F, Gao F, Reed B C, Huete A 2003 Remote Sensing of Environment 84 471-475
[13] Chinese Meteorological Administration 1993 Specifications for ground agricultural meteorological observation (1st). Beijing: China Meteorological Press.
[14] Wang P, Liang H, Li Y, Zhang J 2011 Resources science 33(10) 1976-1983 (in Chinese with English abstract)
[15] Shuai Y 2010 Dissertation thesis, Department of Geography and Environment, Boston University.
[16] Schaaf C B, Gao F, Strahler A H, et al. 2002 Remote Sensing of Environment 83 135-148
[17] http://cimss.ssec.wisc.edu/imapp/db_brdf_v1.0.shtml
[18] Morisette J T, Richardson A D, Knapp A K, Fisher J I, Graham E A, Abatzoglou J, Wilson B E, Breshears D D, Henebry G M, Hanes J M, Liang L 2009 Frontiers in Ecology and the Environment doi:10.1890/070217
[19] Huete A, Didan K, Miura T, Rodriguez E P, Gao X and Ferreira L G 2002 Remote Sensing of Environment 83 195-213
[20] Gao B C 1996 Remote sensing of environment 58 257-266
[21] Moody A, and Strahler A H 1994 International Journal of Remote Sensing 15 3473-3491
[22] Leroy M, and Hautecoeur O 1999 IEEE Transaction on Geoscience and Remote Sensing 37 1698-1708