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Cloud cover throughout the agricultural growing season: Impacts on passive optical earth observations

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ABSTRACT

Cloud cover impedes optical satellite remote sensing instruments from obtaining clear views of the Earth's surface. Meanwhile, agriculture is a highly dynamic process, with significant changes in crop biomass and condition often occurring within roughly a week. The Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) Initiative represents international efforts to improve the satellite-based monitoring of agricultural processes at multiple temporal and spatial scales. Within this context, it is necessary to understand how cloud cover impacts the probability of securing reasonably clear views of croplands using passive optical Earth observations as the agricultural growing season progresses. To this end, we employ 10–13 years of twice daily 0.05° MODIS Terra (AM) and Aqua (PM) surface reflectance quality assessment cloud flags to investigate diurnal, geographical, and seasonal (early, mid, late, and non-agricultural growing season) characteristics of cloud cover presence frequency and pervasiveness (amount) over global agricultural areas. To provide insight into the ability of hypothetical missions with two modeled revisit frequencies ($f = 2, 4$ days) to return reasonably clear views at a rate sufficient to track changes in crop biomass and condition, we show the percentage of 8 day compositing periods throughout the agricultural growing season for which a given clarity requirement (at least 70%, 80%, 90%, or 100% cloud-free) could be met.

This research shows that the early and mid-agricultural growing season, which are important periods for crop type area identification and crop yield forecasting, are characterized by both frequent and pervasive cloud extent. Many important agricultural areas during this and other portions of the agricultural growing season are so persistently and pervasively occluded by clouds that less than half of their 8 day composites would be even 70% clear, suggesting that in these areas/time periods, optical, polar-orbiting imaging is not likely to be a viable option for operational monitoring and alternatives (e.g. microwave synthetic aperture radar, SAR) ought to be considered. Further, for most agricultural areas of the world, regardless of seasonality, morning acquisitions are more likely to return reasonably clear views, an important consideration in the planning of future optical, polar-orbiting Earth observing missions with agricultural monitoring science objectives. These results are an important contribution toward the articulation of Earth observation data requirements for global agricultural monitoring.

1. Introduction & background

Cloud cover impedes optical instruments from obtaining clear views of the Earth's surface. This occlusion has been a persistent barrier to operational monitoring of croplands for many regions of the world, as significant changes in crop biomass can occur within a week (Duveiller, López-Lozano, Seguini, Bojanowski, & Baruth, 2013). Meanwhile, current and near-term polar-orbiting optical moderate spatial resolution (10–70 m) satellite imaging observatories have a revisit capability of 5 (Resourcesat-2 Advanced Wide Field Imaging Spectrometer [AWiFS] alone; upcoming Sentinel-2A/2B, combined) to 8 days (Landsat 7 Enhanced Thematic Mapper [ETM+] & Landsat 8 Operational Land Imager [OLI], combined), meaning cloud cover can limit the capability of these systems to secure reasonably clear views of cropped surfaces with sufficient frequency to monitor these changes. In order to improve the quality of agricultural monitoring information in the context of the Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM), the provision of satellite data necessary to meet agricultural monitoring Earth observation (EO) needs must be ensured (Singh Parihar et al., 2012). This is partially enabled through an analysis of the degree to which cloud cover obscures data acquired over major agricultural areas throughout the agricultural growing season, thereby informing temporal resolution requirements for optical data.

Cloud cover varies throughout the day, over geographic space, and throughout the year, following broad brush patterns (Cairns, 1995;

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Mercury et al., 2012; Minnis & Harrison, 1984; Roy, Lewis, Schaaf, Devadiga, & Boschetti, 2006; Wylie, Jackson, Menzel, & Bates, 2005; Wylie & Menzel, 1999). Very broadly speaking, the afternoon is cloudier than the morning (Cairns, 1995; Minnis et al., 2008), the Equatorial zone and very high-latitudes are cloudier than mid-latitudes, and clouds vary seasonally — all important considerations both in incorporating existing missions into an acquisition strategy as well as in planning for future missions. However, in the context of articulating EO requirements specifically for agricultural monitoring, it is necessary to determine with greater spatial precision how cloud cover varies throughout the agricultural growing season and in turn impacts optical data acquisitions of the cropped land surface. To this end, this present analysis draws upon the growing season calendars' phenological transitions dates (PTDs; Table 1) described in Whitcraft, Becker-Reshef, and Justice (2014), which utilized 10 years (2001–2010) of MODIS NDVI to generate 0.5° agricultural growing season calendars for major producing areas worldwide. We aim to characterize usual cloud cover over agricultural areas of the Earth between these different PTDs (periods ranging broadly from several weeks to several months, depending on location), as well as its impact upon obtaining clear views of the Earth's surface when collecting data in the visible, reflected infrared, and thermal infrared portions of the electromagnetic spectrum.

There have been multiple studies of cloud cover as it varies diurnally (Cairns, 1995; Kaufman et al., 2005; Minnis & Harrison, 1984), seasonally or intra-annually (Gunderson & Chodas, 2011; Ju & Roy, 2008; Wylie & Menzel, 1999; Wylie et al., 2005), and between different sensors (Chernokulsky & Mokhov, 2009; Minnis et al., 2008, 2011; Stubenrauch et al., 2013). Meanwhile, a handful of studies have looked specifically at cloud cover's impacts on a missions' ability to meet their science objectives (Gunderson & Chodas, 2011; Ju & Roy, 2008; Mercury et al., 2012; Roy et al., 2006) including the Landsat program's Long-term Acquisition Plan (LTAP), which compares usual cloud cover information with near-term daily predictions of cloud cover for an area for real-time acquisition scheduling (Arvidson, Gasch, & Goward, 2001; Arvidson, Goward, Gasch, & Williams, 2006; Irish, Barker, Goward, & Arvidson, 2006). Ju and Roy (2008) found that monitoring applications that required more than one cloud-free Landsat ETM + image per year would be severely limited due to cloud cover coupled with on-board data storage limitations. Considering that virtually all agricultural monitoring applications require more than one image during the agricultural growing season, with many of them requiring bi-weekly, weekly, or even more frequent temporal sampling of an area to monitor crop condition, forecast crop yield, and provide early warning of crop failure, cloud contamination of optical imagery presents a major limitation and supports the perspective that an imaging constellation of sensors with multiple overpass times is necessary for agricultural monitoring (Gao, Masek, Schwaller, & Hall, 2006; Goward, Arvidson, Williams, Irish, & Irons, 2009; Goward, Williams, Arvidson, & Irons, 2011; Goward et al., 2012; Ju & Roy, 2008; Roy et al., 2006; Singh Parihar et al., 2012). However, to date no studies have approached the issue of cloud obscuration of optical imagery at the global scale specifically from the perspective of main producing agricultural regions, agricultural growing seasons, and agricultural monitoring.

Table 1
Phenological transition dates (PTDs), and their definitions, as used herein to characterize and subdivide the agricultural growing season (Whitcraft et al., 2014).

PTD parameter name	PTD parameter definition
Start of Season (SOS)	Greenness onset; emergence of above ground biomass; first point at which an upward trending NDVI which precedes the NDVI maximum (peak) surpasses a given threshold
Peak Period Start (PPS)	Onset of green leaf area maximum; start of the period during which the NDVI maximum is likely to occur; first point above 75% of annual range in NDVI which precedes the NDVI maximum (peak)
Peak Period End (PPE)	Onset of senescence; end of the period during which the NDVI maximum is likely to occur; last point above 75% of annual range in NDVI which follows the NDVI maximum (peak)
End of Season (EOS)	End of senescence; termination of photosynthetic activity; last point at which a downward trending NDVI which follows the NDVI maximum (peak) dips below a given threshold

The spatial resolution of analysis is an important factor to consider, as the information must be at a sufficiently fine resolution to be scalable to the multiple swath widths which exist on current and near-term very fine to moderate spatial resolution missions (<100 m spatial resolution, corresponding with swath widths of approximately 11 km [Ikonos] to 740 km [AWiFS]). For this reason, 0.05° (~5.6 km at the Equator) has been chosen. A second factor which merits consideration is the acceptable threshold of cloud amount for each monitoring application, which varies based on monitoring activity, and has to date not been thoroughly researched in the formal literature. To indicate how frequently a completely clear view can probabilistically be obtained, we analyze the probability of a cloud free clear view over 0.05° throughout different portions of the agricultural growing season as well as for each month of the year (herein denoted as "*P*(clear)", shorthand for "probability of clear view"). This effectively provides the upper boundary of required image frequency (the "worst case scenario") by accepting only completely clear 0.05° cells. However, multi-date image compositing is a common approach for studies which do not rely on very fine temporal resolution analyses of phenological progress to separate characteristics (Becker-Reshef, Vermote, Lindeman, & Justice, 2010; Roy et al., 2010), and thus we perform an additional analysis of the portions of scenes which are clear and can be used to create multi-date image composites with varying thresholds of acceptable clarity. Accordingly, the average percentage of each 0.05° which is clear throughout the agricultural growing season is investigated as well (herein denoted as "APClear," shorthand for "average percentage clear"). While at the local level cloudiness in agricultural areas is well-understood, this study presents the global perspective, providing information which is suitable and necessary for incorporation into an image acquisition strategy for global monitoring of areas of large scale agriculture, in the context of GEOGLAM.

2. Methods

Both MODIS Terra and MODIS Aqua cloud cover detections have been shown to compare well with existing cloud cover datasets such as International Satellite Cloud Climatology Project (ISCCP) (Rossow & Schiffer, 1999) and High-resolution Infrared Radiation Sounder (HIRS) (Wylie et al., 2005), with the primary differences in cloud coverage occurring in high latitudes or during winter due to high zenith angles (Chernokulsky & Mokhov, 2009; Mercury et al., 2012). As the majority of croplands fall between 60° N and 60° S (according to Fritz et al. (2013) cropland mask), and those that lie in cold climates are typically dormant/not actively cropped with food crops that impact global food supply during the winter months, these dissimilarities relative to HIRS and ISCCP are not impactful.

For consistency, the baseline dataset for both analyses was 1 km surface reflectance cloud flags from the state QA layer (Vermote, El Saleous, & Justice, 2002) from MODIS Aqua (MYD09) for the afternoon analysis (overpass = 1:30 PM local solar time), and from MODIS Terra (MOD09) for the morning analysis (overpass = 10:30 AM local solar time). Although extensively validated (Kotchenova & Vermote, 2007; Kotchenova, Vermote, Matarrese, & Klemm, 2006; Vermote & Kotchenova, 2008), the MOD09 products may themselves include errors in cloud detection as a result of variable sensitivities to different cloud properties. This and the time it takes for a scan to be completed across swath (clouds move, as well) may introduce bias into the analysis (Kaufman et al., 2005; Mercury et al., 2012; Roy et al., 2006).

Further, in order to understand cloud cover over main producing agricultural areas during different portions of the agricultural growing season, both analyses have been masked using a "best-available" global