NOAA NESDIS

CENTER FOR SATELLITE APPLICATIONS AND RESEARCH

VIIRS-NPP Vegetation Health Products (VIIRS-VH) ALGORITHM THEORETICAL BASIS DOCUMENT

Version 2.1

VIIRS-VH ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 2.1

AUTHORS:

Felix Kogan (STAR)

Wei Guo (IMSG)

Wenze Yang (IMSG)

Hanjun Ding (OSPO)

VIIRS-VH ALGORITHM THEORETICAL BASIS DOCUMENT
VERSION HISTORY SUMMARY

Version	Description	Revised Sections	Date
1.0	New document adapted from NDE guidelines for VIIRS-VH PDR	New Document	12/24/2013
2.0	Updated document for updated 1km and 4km VIIRS-VH ARR	Updated Document	11/20/2017
2.1	Updated document for updated 1km and 4km VIIRS-VH ARR	Updated Document	12/03/2021

Table of Contents

List of Figures

List of Table

ABSTRACT

This document is the Algorithm Theoretical Basis Document (**ATBD**) for the NPP-VIIRS Vegetation Health Operational Product (**VIIRS-VH**) System developed by the NOAA/NESDIS Center for Satellite Applications and Research (**STAR**). The main function of the VIIRS-VH is to produce **surface vegetation health indices** from observation of the Visible Infrared Imaging Radiometer Suite (VIIRS) for applications in numerical weather and seasonal climate prediction models at the National Centers for Environmental Prediction, Climate Prediction Center (**NCEP/CPC**) and **USDA/WAOB**. The VIIRS is currently flying on the Suomi National Polar-orbiting Partnership (**NPP**) spacecraft and will be eventually onboard the **next generation** weather and environmental forecasting Joint Polar Satellite System (JPSS). The retrieval algorithm used in VIIRS-VH is the Multi-Channel Retrieval (MCR) algorithm, similar to the **prototype VH** product derived from Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA polar-orbiting satellites. VH will **use VIIRS's** visible (VIS: 0.6 μm), near-infrared (NIR: 0.8 μm) and thermal (IR: 10-12 μm) bands. This document describes the details of the **algorithm**. To meet the data needs of NCEP and other potential users, the VIIRS-VH was designed as a **global weekly** composite product. Details of these products are presented in Sections 2 and 3 of this document.

VIIRS-VH system was developed/extended from the VH system for AVHRR (VHP 2.0). It is an updated version of VHP.

1 INTRODUCTION

NOAA has developed a new AVHRR-based operational data and products named Vegetation Health Product (**VHP**). The **VIIRS-VH** provides continuous operational service from Suomi NPP. It takes advantage of long-term global AVHRR records (**37-year**), and high resolution (**375 m**) of VIIRS measurements. It contains **data and products** from infrared channels, radiances, indices (raw and with suppressed noise), biophysical climatology, and products. **Applications** include monitoring the environmental and socioeconomic activities (Kogan 1995, 1997, 2015, 2017, 2019, 2020). The algorithm and validation have been developed by scientists and developers of **STAR** VHP team led by Dr. Felix Kogan (Kogan et al. 2015, Yang et al., 2018, 2020, 2021). The Office of Satellite and Product Operations (**OSPO**) will be responsible for data dissemination.

1.1 Purpose of This Document

The purpose of this document is to describe the **VIIRS-VH algorithm** in detail to be used in JPSS-02 VIIRS vegetation health products.

1.2 Who Should Use This Document

The intended users of this document include customers, NDE ARR reviewers, data users and processing system operators of VIIRS-NPP.

1.3 Inside Each Section

This document contains the following sections:

Section 1.0 **– Introduction:** Section 1 provides the purpose, intended users, and revision history of the ATBD.

Section 2.0 – VIIRS-VH **System Overview**: Section 2 describes the products generated by the algorithm and the characteristics of the instruments that supply inputs to the algorithm.

Section 3.0 - **Algorithm Description**: Section 3 describes the algorithm, including a processing overview, input data, physical description, mathematical description, algorithm output, performance estimates, practical considerations, and validation.

Section 4.0 - **Assumptions and Limitations**: Section 4 states assumptions that were made in determining that the software system architecture as designed will meet the requirements, and states limitations that may impact on the system's ability to meet requirements.

Section 5.0 - **Risk**: Section 5 describes algorithm and other risks and actions planned to reduce the risks,

Section 6.0 - **Dissemination**: Section 6 provides a list of references cited in the document.

1.4 Revision History

The original version (Version 2.0), dated November 20, 2017 was **produced** and was presented at the ARR (November 30, 2017) for review.

Updates will be incorporated into this document as the project progresses.

2 VHP OVERVIEW

2.1 Objectives of Vegetation Health Retrievals

The VIIRS Vegetation Health Product (VIIRS-VH) system was designed to meet the user request # 1105-0004 (NWS/NCEP/CPC) and 1105-0009 (USDA/FAS & WAOB) in the NESDIS Satellite Products and Services Review Board (SPSRB) Request Tracking System.

One of the most important long-term (**37-year**) satellite-based data records characterizing land surface, air temperature near the ground and climate was created from the Advanced Very High Resolution Radiometer (AVHRR) flown on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Several **global data sets** have been developed from the AVHRR records since the early 1980s. They were the NOAA's Global Vegetation Index (GVI and GVI-2), National Aeronautics and Space Administration (NASA)'s Pathfinder, GIMMS and LTDR (Tarpley et al 1984, James and Kalluri 1994, Kidwell 1997, Tucker et al 2004). These datasets focused only on the Normalized Difference Vegetation Index (**NDVI**), ignoring infrared measurements, which are very useful for monitoring land, climate and socioeconomics. Therefore, NOAA developed a dataset entitled the Global Vegetation Health Product (**VHP**). The VHP has advantages over other long-term global data sets, being the **longest** (37-year), having the highest spatial resolution (**4-km**), containing, in addition to **NDVI**, data and products from infrared channels, originally observed reflectance and **emission**, many indices with suppressed noise, biophysical **climatology** and more importantly, **products** used for monitoring environmental and socioeconomic activities (Kogan 1995, 1997).

In October 2011, NOAA/NESDIS launched the new generation of satellites (NPP-JPSS) with the most advanced **VIIRS** sensor on board which provides much **better quality** data sets and products including the vegetation health product. In the future, AVHRR is expected to be replaced by VIIRS or its successor. For continuity purpose, it is desirable to have vegetation health product derived from VIIRS using the similar algorithm as VHP from AVHRR. Since VIIRS is different than AVHRR, considerable adjustments are required in order to have continuous and un-interrupted flow of VH data with better quality, higher resolution and in the form to enable users to provide timely assessments.

In December 2013, the program for producing VH from VIIRS was named as "**VIIRS-VH**". It was developed from existing operational AVHRR-VH system (VHP 2.0). All functions of VHP are retained and/or upgraded. It can produce vegetation health product from either VIIRS or AVHRR with various output resolutions.

During 2017, substancial updates have been applied to VIIRS-VH product. Major updates include (1) adapting a set of **pseudo long-term VIIRS climatology**, so that the VIIRS-VH can be directly calculated from VIIRS smoothed NDVI and brightness temperature (BT), without converting them to AVHRR counterparts; and (2) extending the VH products to **1 km spatial resolution**.

2.2 Instrument Characteristics

Vegetation Health product (VHP) requires the Normalized Difference Vegetation Index (NDVI) data for estimating the vegetation moisture condition and Brightness Temperature (BT) from infrared bands for estimating the surface thermal condition.

For AVHRR-VHP product, these parameters were **retrieved** from the AVHRR onboard all NOAA polar-orbiting Satellites. NOAA-19 satellite is currently the operational primary satellite for NOAA weather monitoring.

The AVHRR is a six channel scanning radiometer providing three solar channels in the visible-near infrared region and three thermal infrared channels (Table 2.1). More information on AVHRR is provided at
http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/html/c7/sec7-1.htm

Table 3.2.1-1 Summary of AVHRR/3 Spectral Channel Characteristics

Parameter	Ch. 1	Ch. 2	Ch. 3A	Ch. 3B	Ch. 4	Ch. 5
Spectral Range (μm)	0.58-0.68	.725-1.1	1.58-1.64	3.55-3.93	10.3-11.3	11.5-12.5
Resolution (km) *	1.09	1.09	1.09	1.09	1.09	1.09

AVHRR-VH uses the AVHRR Global Area Coverage (GAC) data, with resolution of 4 km at equator.

The Visible Infrared Imager Radiometer Suite (**VIIRS**) provides **advanced imaging and radiometric capabilities** from NPP spacecraft and the next generation JPSS.

VIIRS Visible and near infrared channels (I1 – 0.64μm, I2 - 0.86μm) are used to produce the NDVI and infrared band (I5 – 11.0-12.0 μm) are used to produce BT. Derived indices from NDVI and BT will be used to develop VH product.

Table 3.2.1-2 Summary of VIIRS Spectral Channel Characteristics

VIIRS Band	Spectral Range (um)	Nadir HSR (m)	MODIS Band(s)	Range	HSR
DNB	0.500 - 0.900				
M1	0.402 - 0.422	750	8	0.405 - 0.420	1000
M2	0.436 - 0.454	750	9	0.438 - 0.448	1000
M3	0.478 - 0.498	750	3 10	0.459 - 0.479 0.483 - 0.493	500 1000
M4	0.545 - 0.565	750	4 or 12	0.545 - 0.565 0.546 - 0.556	500 1000
I1	0.600 - 0.680	375	1	0.620 - 0.670	250
M5	0.662 - 0.682	750	13 or 14	0.662 - 0.672 0.673 - 0.683	1000 1000
M6	0.739 - 0.754	750	15	0.743 - 0.753	1000
I2	0.846 - 0.885	375	2	0.841 - 0.876	250
M7	0.846 - 0.885	750	16 or 2	0.862 - 0.877 0.841 - 0.876	1000 250
M8	1.230 - 1.250	750	5	SAME	500
M9	1.371 - 1.386	750	26	1.360 - 1.390	1000
I3	1.580 - 1.640	375	6	1.628 - 1.652	500
M10	1.580 - 1.640	750	6	1.628 - 1.652	500
M11	2.225 - 2.275	750	7	2.105 - 2.155	500
I4	3.550 - 3.930	375	20	3.660 - 3.840	1000
M12	3.660 - 3.840	750	20	SAME	1000
M13	3.973 - 4.128	750	21 or 22	3.929 - 3.989 3.929 - 3.989	1000 1000
M14	8.400 - 8.700	750	29	SAME	1000
M15	10.263 - 11.263	750	31	10.780 - 11.280	1000
I5	10.500 - 12.400	375	31 or 32	10.780 - 11.280 11.770 - 12.270	1000 1000
M16	11.538 - 12.488	750	32	11.770 - 12.270	1000

NDVI is a combination of VIS and NIR bands. For VIIRS: band I1, RED and band I2, NIR.

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \qquad (2.1)$$

Brightness temperature from VIIRS image band 5 (AVHRR channel 4) is used to characterize the surface thermal condition.

3 ALGORITHM DESCRIPTION

3.1 Processing Outline

The VIIRS-VH system generates weekly VCI, TCI and VHI through the following steps:

Step 1: Retrieval of VIIRS I1, I2, I5 radiances and solar & satellite geometry angles from the Scientific Data Records (SDR) granules and mapped into geographic grid (GG) or Plate Carrée projection.
Step 2: Filing gaps
Step 3: Development of daily map
Step 4: Development of weekly composite map by selecting the pixels with maximum NDVI value from 7-day maps.
Step 5: Calculation of NDVI (from I1 and I2) and BT (from I5)
Step 6: Noise removal from NDVI and BT
Step 7: Calculate **VIIRS climatology** of NDVI and BT based on three biophysical laws (Law of Minimum, Law of Tolerance and Carrying Capacity).
Step 8: Update short-term VIIRS climatology to long-term VIIRS climatology, using information from AVHRR climatology.
Step 9: Calculate three VH indices: Vegetation Condition Index (VCI), Thermal Condition Index (TCI) and Vegetation Health Index (VHI).

The data flow chart for AVHRR-VH and VIIRS-VH are shown in Figure 3.1-1 and Figure 3.1-2 respectively.

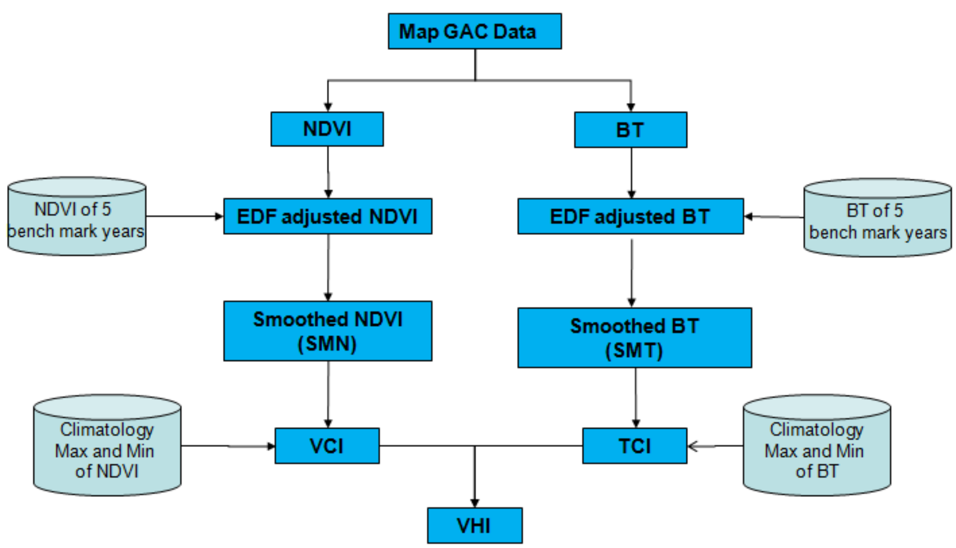


Figure 3.1-1 Data flow chart of AVHRR-VH

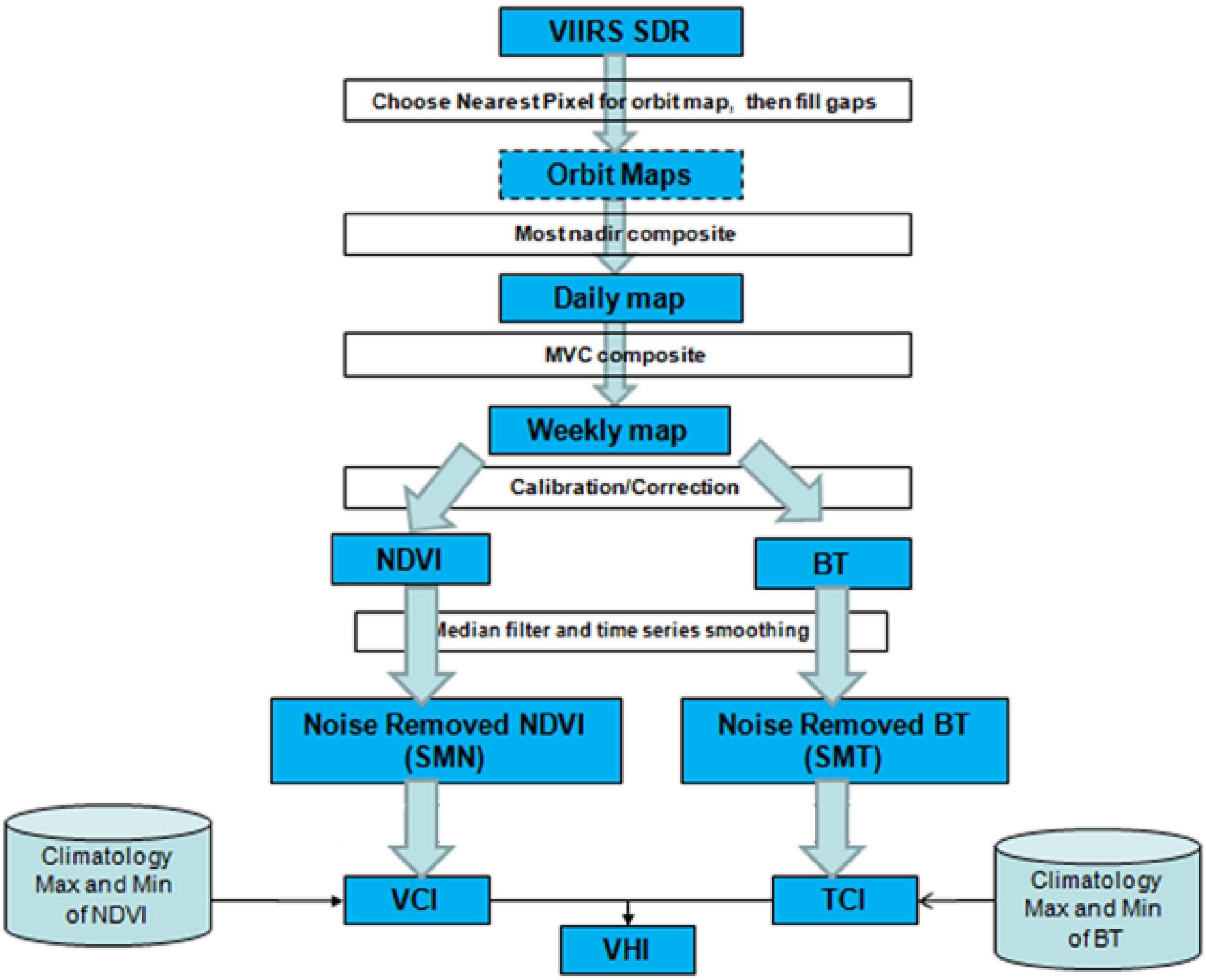


Figure 3.1-2 Data Flow chart for VIIRS VH

3.2 Algorithm Input

3.2.1 Reflectance of visible and near infrared bands

VIIRS visible (I1), near infrared (I2) and infrared (I5) from SDR files are used. They are organized by 6 data types and 1014 granules.

- **SVI01:** reflectance of image band 1
- **SVI02:** reflectance of image band 2
- SVM03: reflectance of moderate band 3 (optional)
- **SVI05**: temperature of image band 5.
- JPSSRR-CLOUDMASK: cloud information

- GITCO: geo-location file, including the data fields: latitude, longitude, solar and sensor zenith angles.

Other optional data generated by JPSS are also used for developing VH products:
- VLSTO: land surface type
- VIVIO: EVI at top of canopy
- VSCMO: snow cover bitmap
- VSTYO: vegetation Fraction and surface type

3.2.2 Brightness Temperature (BT)

VIIRS images band (I5 – 10.0-12.0 μm) is used to produce BT.

3.2.3 Ancillary Data

The ancillary data for the VIIRS-VH algorithm include land cover map and climatology map.

3.2.3.1 USGS land sea mask map

USGS land sea mask is in geographic grid (equal lat-lon) of 43200 columns and 21600 rows, with resolution of 30 seconds. It covers full surface of the earth, latitude range: [-90S to 90N], longitude range: [-180,180]. The first pixel is at [-180,90N]. Original data is downloaded from USGS web site. It was re-formatted to bit map and saved as HDF file. This file will be used as input when making daily and weekly composite maps.

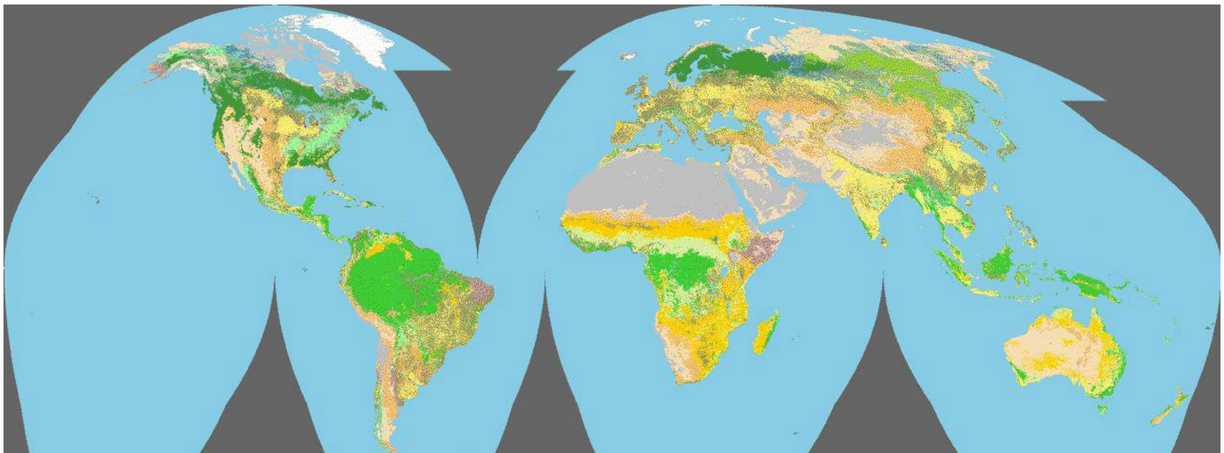
- landseamaskll.bit.hdf 3MB.

3.2.3.2 High resolution land sea mask derived from high resolution MODIS NDVI.

MODIS 2002 to 2012 16-day composite NDVI was used to generate high resolution land sea mask. MODIS NDVI was first re-projected to 500 m GG, then set the land sea flag as land (1) if a pixel has a valid NDVI value in any composite period in the ten years. When processing raw NDVI and BT ("ND" file) with high resolution (example: 500 m) from VIIRS, it will be used to set land sea flag in QA data set. This dataset was saved in 8x8 tiles.
- modis_landmask/landsea_fromNDVI.G500m_r01c01.hdf

3.2.3.3 Land cover map

The International Geosphere-Biosphere Programme (**IGBP**) Land Cover map, i.e. Global Land Cover Characteristics Data Base (GLCC) was used. This clutter model provides global coverage at a 30 arc second resolution using 17 clutter categories. Details are available at http://edc2.usgs.gov/glcc/ . The database consists of a single file - gigbp2_0ll.img (933,120,000 bytes). This file can be downloaded in a zipped format from http://edcftp.cr.usgs.gov/pub/data/glcc/globe/latlon/gigbp2_0ll.img.gz.



International Geo-sphere Biosphere Program (IGBP) Global Land Cover Legend

Code	Class Name
0	INTERRUPTED AREAS (GLOBAL GOODES HOMOLOSINE PROJECTION)
1	EVERGREEN NEEDLELEAF FOREST
2	EVERGREEN BROADLEAF FOREST
3	DECIDUOUS NEEDLELEAF FOREST
4	DECIDUOUS BROADLEAF FOREST
5	MIXED FORESTS
6	CLOSED SHRUBLANDS
7	OPEN SHRUBLANDS
8	WOODY SAVANNAS
9	SAVANNAS
10	GRASSLANDS
11	PERMANENT WETLANDS
12	CROPLANDS
13	URBAN AND BUILT-UP
14	CROPLAND/NATURAL VEGETATION MOSAIC
15	SNOW AND ICE
16	BARREN OR SPARSELY VEGETATED
17	WATER BODIES
100	NO DATA

(ftp://edcftp.cr.usgs.gov/pub/data/glcc/globe/latlon/igbp2_0.leg)

Figure 3.2-1 IGBP Land Cover Map

3.2.3.4 GlobCover Land Cover Maps

The 300m resolution GlobCover Land Cover Maps was used for finer resolution VIIRS-VHP products. The land cover map is derived by an automatic and regionally-tuned classification of a time series of global MERIS FR mosaics for the year 2009. The global land cover map counts 22 land cover classes defined with the United Nations (UN) Land Cover Classification System (LCCS). Details are available at http://due.esrin.esa.int/page_globcover.php.

3.2.3.5 Climatology of NDVI and BT

Three climatology (maximum, minimum, mean and standard deviation) maps were generated from no noise weekly NDVI and BT for different years, they are 1) 36-year AVHRR climatology (A36), 2) 5-year AVHRR climatology (A5), and 3) 5-year VIIRS climatology (V5). Together they are used to derive a pseudo 36-year VIIRS climatology, as described in section 3.3.6 and Yang et al., 2018.

3.2.3.6 Calibration parameters

For VIIRS, reflectance factors were provided in VIIRS SDR file, which are used to calculate calibrated reflectance.

3.3 Theoretical Description of VHP and VH Method

After noise removal (see 3.3.5), weather-driven differences in NDVI and BT between the years become apparent: lower NDVI and higher BT in dry years and opposite in normal and wet years. This principle of comparing NDVI and BT for a particular year with their dry-wet range calculated from 30-year observations was laid down in the VH algorithm development and were based on the three laws: Law-of-Minimum, Law –of –Tolerance and Carrying Capacity. The absolute maximum and minimum of NDVI and BT during 1981-2005 were calculated for each of the 52 weeks and for each pixel. They were then used as the criteria to estimate the upper (favorable weather) and the lower (unfavorable weather) limits of the ecosystem resources. Further, for estimation of weather impacts on vegetation condition, NDVI and BT values for a particular time (year and week) were normalized relative to the absolute max/min interval. Following this procedure, NDVI and BT were rescaled based on equations (3.1-3.1). They were named the Vegetation Condition Index (VCI), Temperature Condition Index (TCI) and Vegetation Health Index (VHI). These indices are designed to characterize moisture (VCI), thermal (TCI) and total vegetation health (VHI) conditions in response to weather impacts

$$VCI=100*(NDVI-NDVImin)/(NDVImax-NDVImin) \quad (3.1)$$

$$TCI=100*(BTmax - BT)/(BTmax - BTmin) \quad (3.2)$$

$$VHI = a*VCI + (1- a)*TCI \quad (3.3)$$

where NDVI, NDVImax, and NDVImin (BT, BTmax, and BTmin) are the noise reduced (smoothed) weekly NDVI (BT), their multi-year absolute maximum, and minimum, respectively. The VCI, TCI and VHI approximate the weather component in NDVI, BT and their combination values. They fluctuate from 0 to 100, reflecting changes in vegetation conditions from extremely bad to optimal. The weighting factor (a) in equation 3.3 was determined by experience, currently, a=0.5).

The quality flags were stored in Quality Assurance (QA) dataset in VH file records if the pixel is over desert, on coastal line, with continues clouds or snow or ice).

3.3.1 Daily map

A daily map is created by projecting satellite observation of a specific day to a predefined grid. This grid is named by “the Global Vegetation Indices” (GVI in the VHP algorithm nomenclature). The area spans from latitude 75.024° N (north) to -55.152° S (south) and from longitude -180° W (west) to 180° E (east). Geographic projection is “Plate Carree” (the sizes of all grid cells are the same degrees in both directions). Further we called this grid as “GVI grid” in VH documents.

3.3.1.1 Variables of VH daily map

Daily map for VH product contains following variables:

- Radiance in VIS, NIR and IR bands
- NDVI and BT
- Sensor and solar zenith and azimuth angles,
- Packed cloud information (serve as quality flags)

3.3.1.2 Two steps procedure for making daily from orbit maps

- First: Make orbit map (an orbit map is part of a daily map; it is composited from the data of an orbit). In order to avoid the overlay of two ends of an orbit any orbit is divided into 2 parts, which are processed separately.
- For orbit map, the pixel closest to the center of a grid cell is normally selected; orbit map will be stored temporary in the memory.
- Fill the internal gaps on an orbit map from the neighboring pixels.
- Second: Merge the orbit maps (about 28 orbit maps/day) to the daily map by comparing the orbit maps and selecting the most nadir pixel.

The Figure 3.3-1 shows that these steps successfully avoids bad data at swath edge (with larger sensor zenith angle), especially for high latitudes. The top panel shows a VIIRS one day RGB color image (band 2, 2 and 1 for red, green and blue guns) composited from orbit maps. Percentage of gaps filled for a selected region is less than 40% for most of area (left bottom). The maximum sensor zenith angle becomes smaller when latitude increasing (right-bottom).

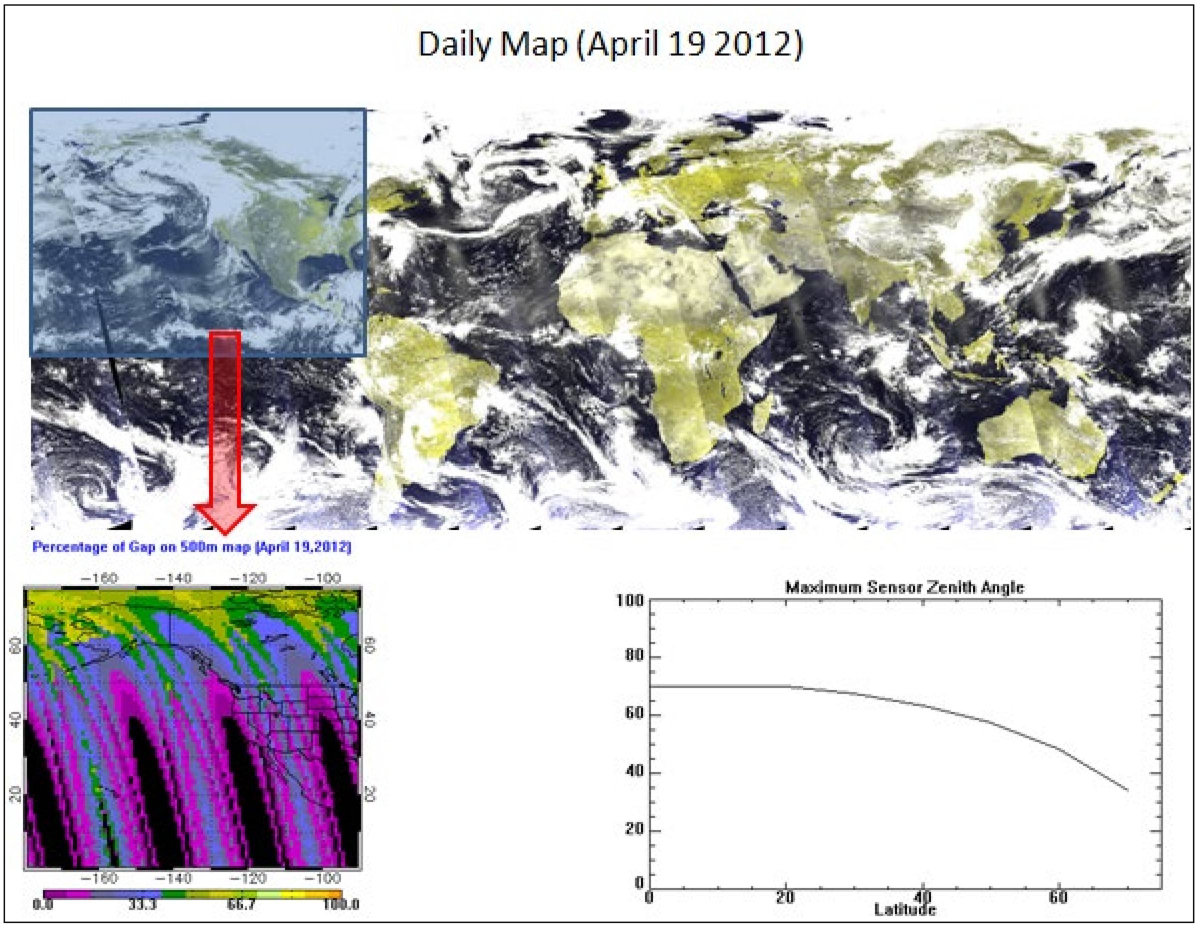


Figure 3.3-1 Statistics on daily map composing

3.3.1.3 Daily map from VIIRS

VIIRS-VH requires the following 6 types of data: SVI01, SVI02 (reflectance of image band 1 and 2), SVI05 (temperature of image band 5), GITCO (geo-location file, including the data fields: latitude, longitude, solar and sensor zenith angles) and JPSSRR-CLOUDMASK (cloud information). Each granule contains 1.4 minutes VIIRS observation. There are about 1014 granules per day. The minimum input VIIRS SDR granules data is about 1 TB.

Figure 3.3-2 shows the concept of algorithm of making VIIRS daily map.

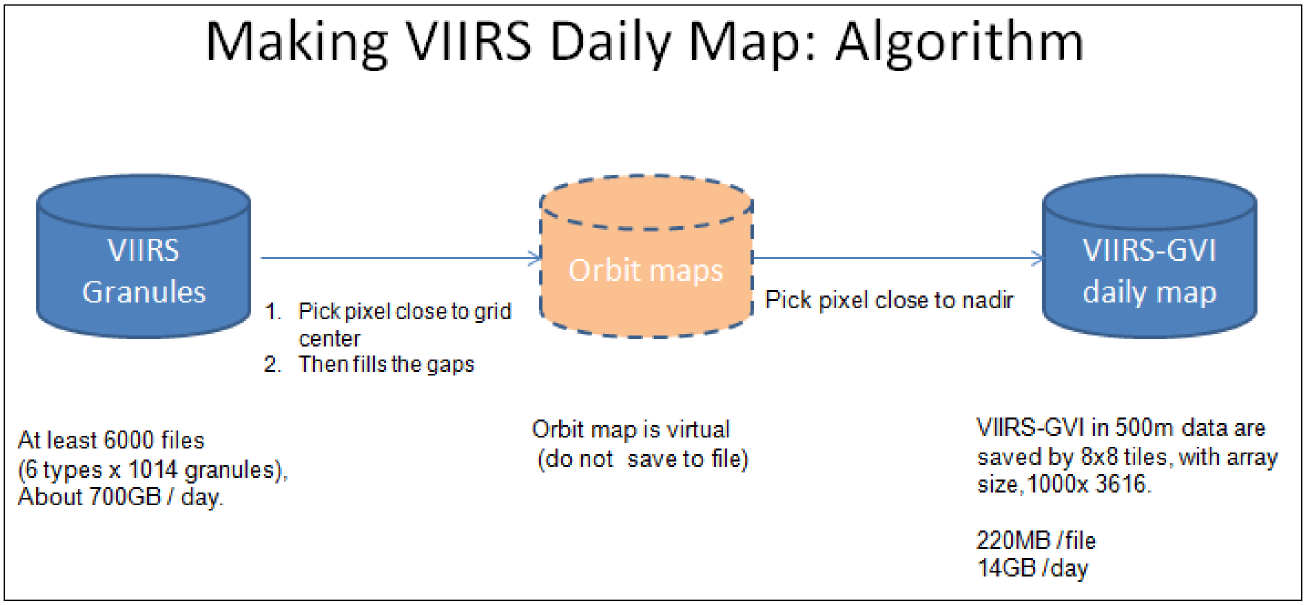


Figure 3.3-2 Concept of the algorithm of making VIIRS daily map.

3.3.2 Weekly Composite Map

Daily maps are aggregated to a seven-day composite map using Maximum Value Composite (MVC) method by saving data of the day with the largest NDVI. The MVC procedure is applied to each pixel. Once a day is derived, all associated variables of this pixel will be copied to the daily map. This ensures that all variables of a given pixel were observed at the same time. The compositing period starts from the first day of a year. The “week” number refers to the sequential 7-day number (“week 1” always covers the period from day 1 to 7 of a year). The VHP weekly composite map contains the same variables as the daily maps. It also contains data fields recording the selected day and the number of days with valid data. This information can be used for evaluation of data quality.

“ValidDaysForCH1”: the number of days with valid data of reflectance at visible band

“cell_jday”: the day of year of the selected pixel.

“packed_cloud_mask”: contains the “packed cloud mask” information of selected pixel.

Figure 3.3-3 shows every day and the weekly composite NDVI images.

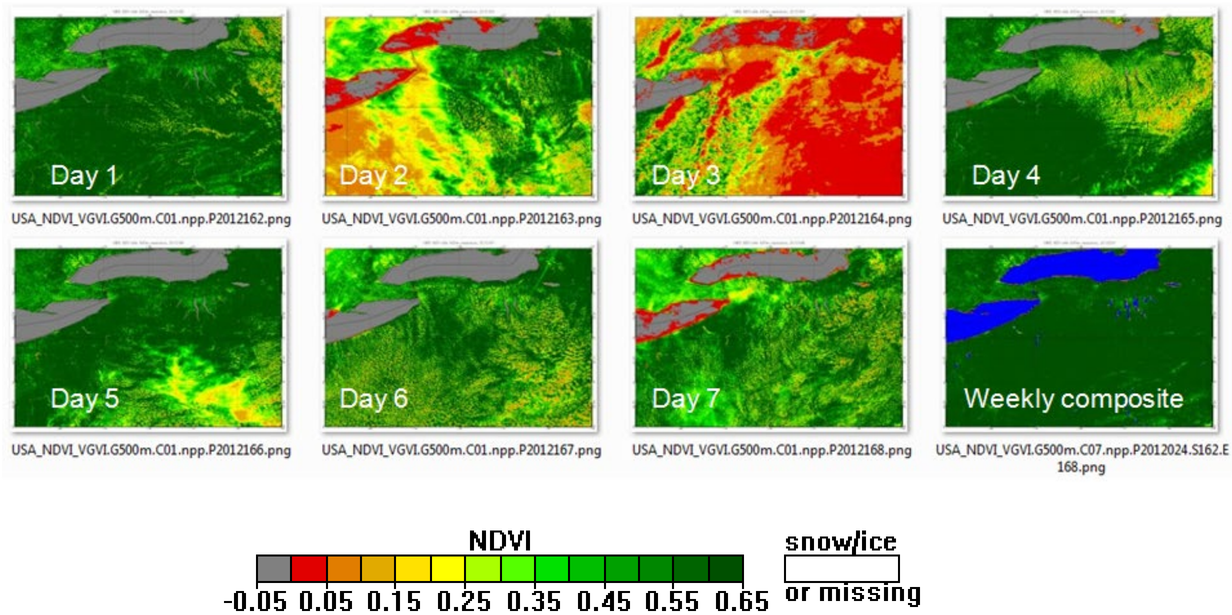


Figure 3.3-3 VIIRS NDVI from daily maps and seven days composite map.

3.3.3 Calibration for reflectance

VIIRS has on board calibration; these parameters are available in the VIIRS SDR file as "reflectance_factors". Reflectance of visible and near infrared are calculated as:

$$\text{Reflectance} = \text{factor}[0] * \text{SI} + \text{factor}[1] \quad (3.5)$$

Where,

factors are "reflectance_factors" with two elements (slope and intercept)

SI is the "scaled integer" stored in VIIRS SDR files.

3.3.4 High frequency noise

Noise in AVHRR data creates fundamental constraints to the remote sensing of the Earth. The noise sources are physical, geometrical, mechanical, mapping, environmental, random etc.; some of them long-term, some short-term and some both (Kogan *et al* 1996, Rao and Chen 1993, 1999, Cracknell 1997, Kidwell 1997). Currently, a complete physically based correction for all effects over various land surfaces, which is able to eliminate high, medium and low frequency noise, is not available (Kogan, 1995). High frequency noise created by clouds, variable transparency of the atmosphere (water vapor, dust, chemicals etc.), surface anisotropy, geometry of the sun and sensor, position of satellite, methods of data processing, random noise (including human errors) distort considerably reflectance/emission of both NDVI and BT creating difficulties for satellite data application.

3.3.5 Noise removal

The vegetation-oriented method for a comprehensive noise reduction stems from a statistical approximation of the vegetation and temperature annual time series. The three goals are pursued (a) single out the seasonal cycle; (b) suppress high frequency noise, and (c) enhance medium and low frequency variations related to large-scale and persistent weather fluctuations. This technique considers smoothing the weekly time series with a combination of a compound median filter and the least squares technique (Kogan et al. 1993). Numerous tests showed that this smoothing eliminated completely the high frequency outliers, including random, approximated accurately the annual NDVI and BT cycles, and, more importantly, singled out medium-to-low frequency weather-related fluctuations (valleys and hills in the NDVI and BT time series) during the annual cycle (Kogan, 1995).

Figure 3.3-4 shows the NDVI and smoothed NDVI derived from AVHRR and VIIRS. Time series smoothing technique successfully removed the noise in time series of NDVI. It also confirms that there is bias between NDVI from these two instruments.

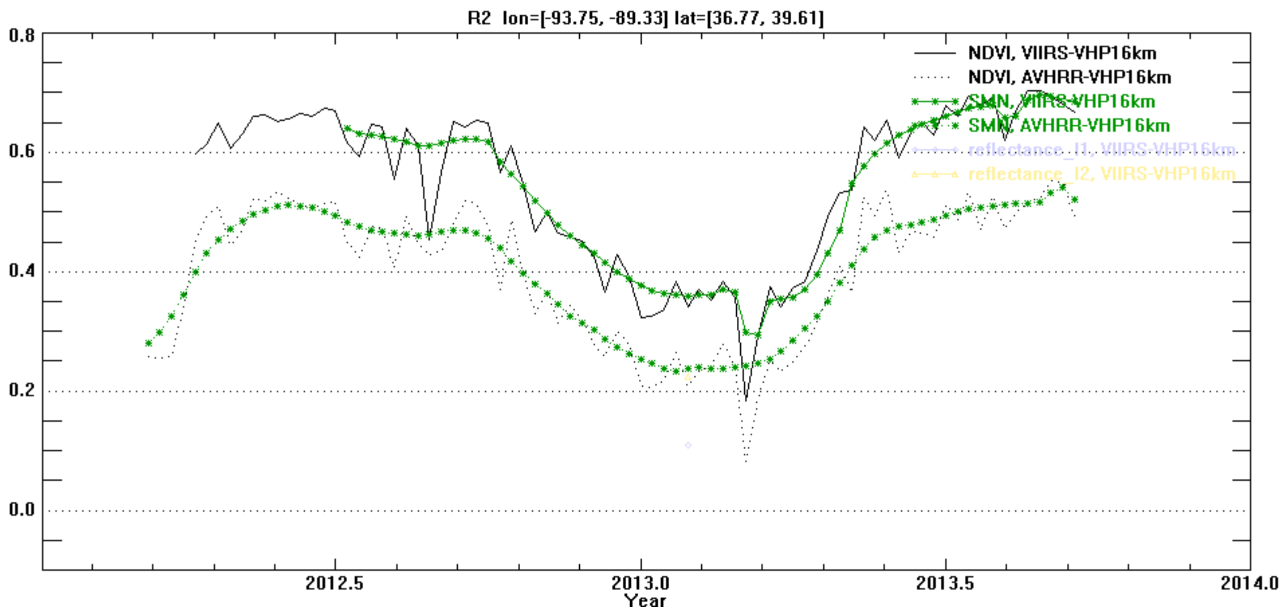


Figure 3.3-4 NDVI and smoothed NDVI derived from AVHRR and VIIRS

3.3.6 4km Climatology

Climatology (multi-year maximum, minimum, mean and standard deviation) of both NDVI and BT are critical for derivation of VH indices. Three 4km climatology (maximum, minimum, mean and standard deviation) maps were generated from no noise weekly NDVI and BT for different years, they are 1) 36-year AVHRR climatology (A36), 2) 5-year AVHRR climatology (A5), and 3) 5-year VIIRS climatology (V5). Together they are used to derive a pseudo 36-year VIIRS climatology.

To build the A36 climatology, the extreme values were chosen from AVHRR onboard different afternoon satellites through time elapse, the periods used for the climatology are selected regarding to the most reliable data quality for each satellite, as listed in Table 3.3.6-1. Note the bias related to sensor degradation, satellite orbital drift, jumps in the indices while transitioning from one satellite to the next/previous and an elevated stratosphere aerosol has been taken care of, according to Kogan et al., 2011.

Table 3.3.6-2 Periods of AVHRR Data Used for 36-Year Climatology

Satellite	Start Year	Start Week	End Year	End Week
NOAA-7	1981	42	1984	50
NOAA-9	1985	15	1987	52
NOAA-11	1989	20	1992	52
NOAA-14	1995	20	1999	52
NOAA-16	2001	20	2002	52
NOAA-18	2006	1	2010	52
NOAA-19	2011	1	2017	3

Considering VIIRS, upon the experiment time for this article, the most reliable data span from Week 45 of 2012 to Week 3 of 2017, approximately 5 years. Similar to A36 climatology, a VIIRS climatology (V5) at 4 km resolution was build based on the actual observation. Yet the V5 VH products represent unsatisfactory characteristics comparing to A36 products, as too many values are close to the extreme ends.

Suppose there is an overlap period between VIIRS and AVHRR, due to excellent linearity and extremely high correlation, it is assumed that whenever AVHRR reaches an extreme, VIIRS would reach its extreme simultaneously. This overlap period could be as short as 5 years, or as long as 36 years, and the ratio of long-term climatology vs. short-term climatology is independent of instrument. So, we may build a short-term AVHRR climatology (A5) using the same period as V5, and construct a long-term VIIRS climatology (V36), as

$$V36 = \frac{A36}{A5} \times V5 \quad (3.6)$$

Note Eq. (3.6) should apply to each week and each pixel.

Figure 3.3-5 compares the several versions of NDVI climatology for the same location. By raising the maximum and lowering the minimum, the range between maximum and minimum is widened from V5 to V36.

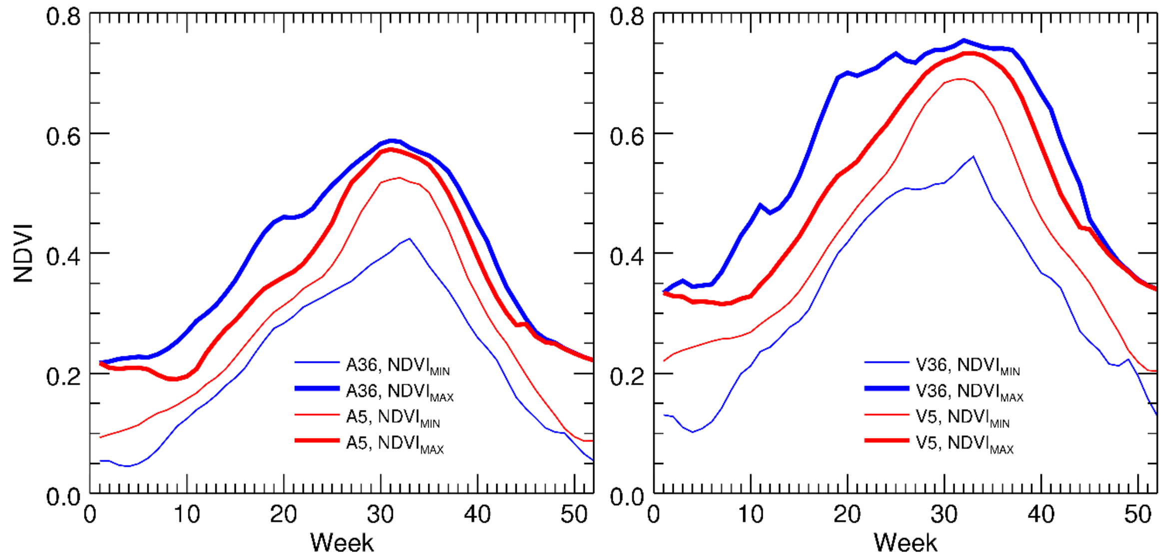


Figure 3.3-5 Comparison of (a) A5 and A36, (b) V5 and V36 NDVI climatology at a crops site in Illinois, USA.

3.3.7 1km Climatology

The approach to derive 1km climatology is illustrated in Figure 3.3-6, the main idea is to add spatial variation onto 4 km resolution VIIRS pseudo 36-year climatology. Essentially, given a base resolution pixel, the spatial variation is calculated as the departure of 1km values from the mean of them. From the available 5-year VIIRS observation, we can directly obtain a temporal weekly mean for each 1km pixel ($V5\ 1km$). As a 4km pixel corresponds to 16 1km pixels, one can calculate the average of these 1km pixels, referred as $V5\ 4km\ Mean$, the departure is simply $V5\ 1km - V5\ 4km\ Mean$. Form another side, one 4km V36 climatology pixel ($V36\ 4km$) can be expanded to 16 1km pixels ($V36\ 1km\ Grid$), by simply repeating the 4km value within the spatial range. Then the outcome long-term 1km climatology ($V36\ 1km$) is the sum of the departure and $V36\ 1km\ Grid$.

In the inland area, there is high probability that all 1km pixels are land pixels, then the above calculation is enough. Yet there is also probability that the 4km pixel is a coastal pixel, then more calculation is needed to improve data quality. For this purpose, the 300 m resolution GlobCover data set (Bicheron et al., 2011; data available from http://due.esrin.esa.int/page_globcover.php) from the European Space Agency (ESA) is used as land/sea mask for calculating the spatial mean, and excluding the 1km water pixels.

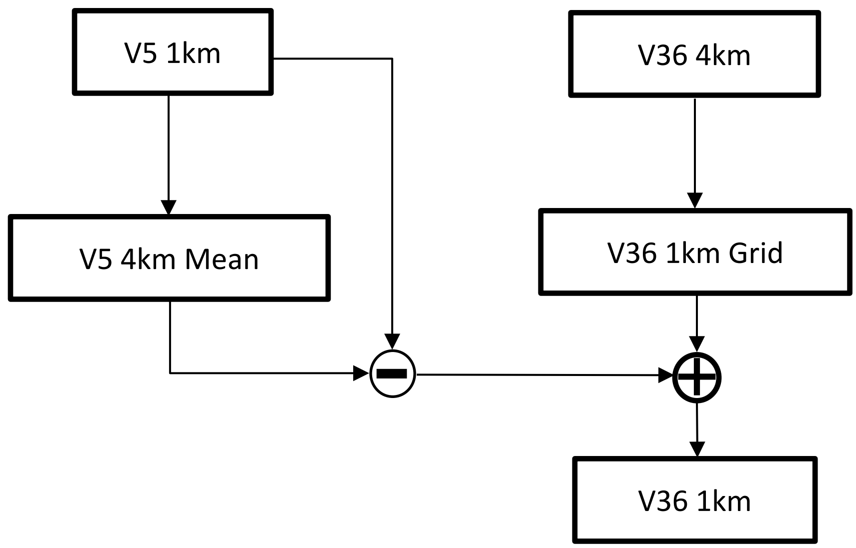


Figure 3.3-6. Flowchart of calculating 1km climatology from VIIRS pseudo 36-year (V36) 4km climatology.

3.4 VIIRS-VH Algorithm Output

The outputs of VIIRS-VH system include:

(1) Three vegetation indices (VCI, TCI, VHI) on 1km GG are stored in a NetCDF file. There is one accompanying data set for quality assurance (QA) stored in the same file. QA flags indicate if there are potential issues on VH products when VH indices are calculated normally.
(2) Three vegetation indices (VCI, TCI, VHI) on 4km GG are stored in a NetCDF file. There is one accompanying data set for quality assurance (QA) stored in the same file. QA flags indicate if there are potential issues on VH products when VH indices are calculated normally.
(3) Images of VCI, TCI, VHI in 16km resolution, stored in PNG file format. Desert or snow/ice areas are masked as grey color to indicate no meaningful retrieval of VH product.
(4) Vegetation indices data in Geo-TIFF.
(5) Metadata: Metadata will be saved as file attributes in each NetCDF file. They are also saved in META data file in XML format together with additional statistic information which is useful to monitor the VHP product data quality and processing status.

3.5 Performance Estimates

By using the climatology data and comprehensive digital filters, the VIIRS-VH system can produce weekly vegetation health indices from VIIRS SDR granules data globally (from 55º S to 75º N).

3.5.1 Test Data Sets

The AVHRR-VHP dataset will be used as test data if needed.

3.5.2 Numerical Computation Considerations

The whole algorithm is composed of many straight forward calculations. There is no special requirement on numerical computation.

3.5.3 Programming and Procedural Considerations

For VIIRS-VH, the input VIIRS SDR data are up to 1TB per day. The code must be efficiently to process data with appropriate latency:

- The software will divide the output data into multiple tiles.
- The software creates a list of input granules. Calculate the position of granules by reading only the four corner points. Find file name for each data type for a given granule; if files are duplicated, keep the one for the latest time.
- Calculating no noise NDVI and BT, update them for the last 8 weeks.

In real time mode: VIIRS-VH code will runs every day to create daily map and once per week to create weekly MVC composite and VH indices.

For VIIRS-VH system one executable will be developed by C++ code:

- "VHsuite.exe"
  Produce daily map and weekly composite from VIIRS SDR granules, and also produce ND, SM and VH files from weekly composite

3.5.4 Quality Assessment and Diagnostics

Unit testing and system testing will include quality assessment with historical in situ observations.

3.5.5 Exception Handling

The expected exceptions, and a description of how they are identified, trapped, and handled, will be provided in a future version of this document.

3.6 Sample Results

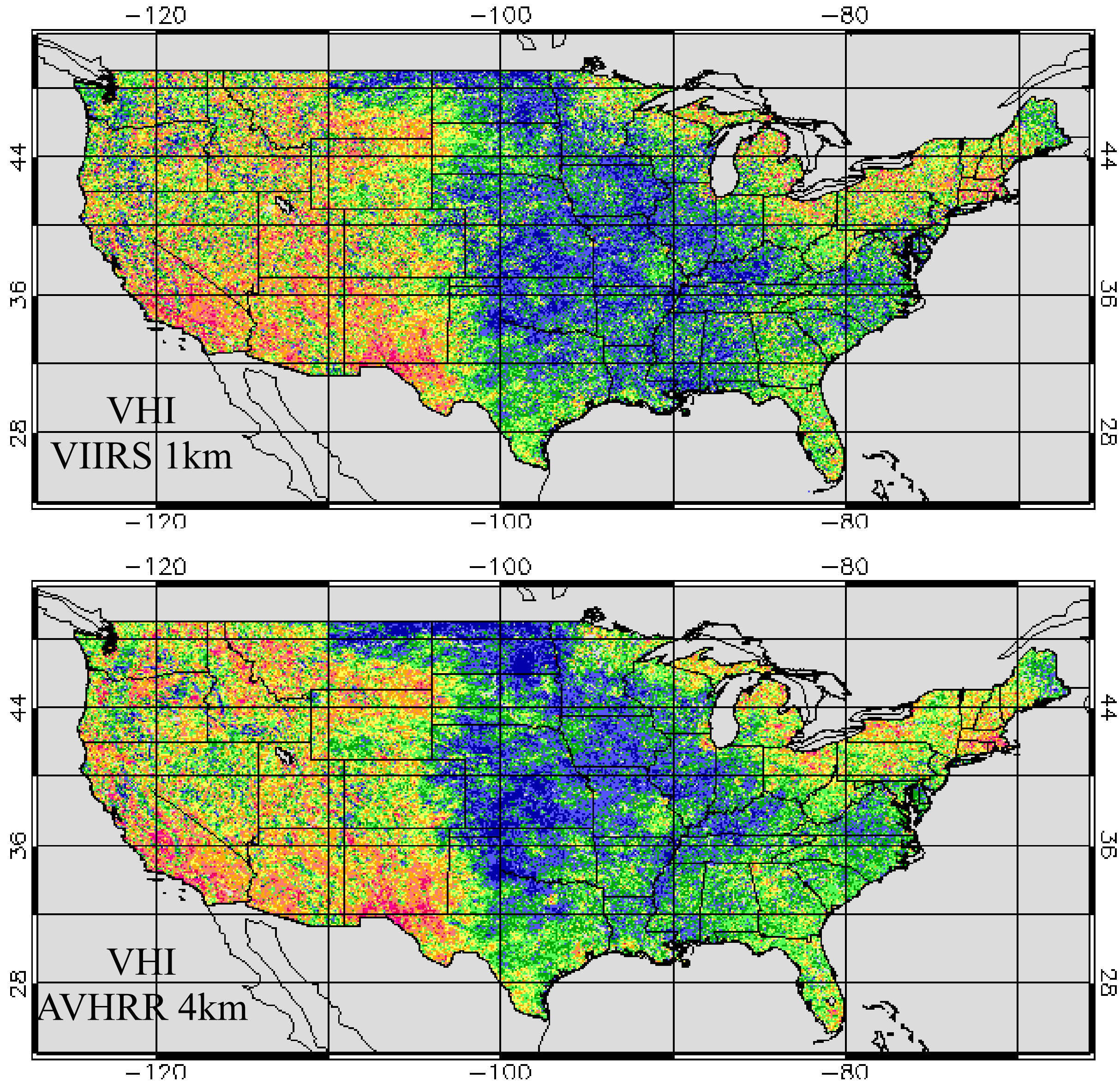


Figure 3.6-1 Vegetation Health maps produced by the VIIRS-VH algorithm at 1km resolution (upper), compared with that produced by the AVHRR-VH algorithm at 4km resolution (lower).

3.7 Validation

Validation of VIIRS-VP will be fulfilled by comparing with VHP product**.**

4 ASSUMPTIONS AND LIMITATIONS

4.1 Assumptions

- Vegetation changes slow over time without large jumps. No noise NDVI is changing similarly. Abnormal jumps in NDVI time series will be considered as noise and be removed.
- The time latency of the VIIRS-VH products is up to 6 hours after the end of each 7-day period. This time will be sufficient to process large amount of VIIRS SDR data.

4.2 Limitations

- The VIIRS-VH will calculate VH indices for all land including non-vegetated areas. Such areas will be flagged.
- The VIIRS VH system will produce VH indices for the global land (55º S to 75º N).

5 RISKS

The real time and climatology data set need to be updated by using most recent dataset. If climatology data is not updated it will impact quality of the VIIRS VH product.

6 LIST OF REFERENCES

Bicheron, P., V. Amberg, L. Bourg, D. Petit, M. Huc, B. Miras, C. Brockmann, O. Hagolle, S. Delwart, F. Ranera, M. Leroy, and O. Arino, 2011: Geolocation assessment of MERIS GlobCover orthorectified products. *IEEE Trans. Geosci. Remote Sens.*, 49(8): 2972-2982.

Cracknell, A.P. 1997: The Advanced Very High resolution Radiometer. Taylor & Francis, USA, 534 p.

Crosby, D. S., Goldberg M. D. and W. Chung 1996, Inter-satellite calibration using empirical distribution functions. 8th Conference on Satellite Meteorology and Ocean, Atlanta GA. *Amer. Meteor. Soc.*, 188-190.

Heidinger, Andrew K. and Pavolonis, Michael J. Global daytime distribution of overlapping cirrus cloud from NOAA's Advanced Very High Resolution Radiometer. *J. Climate, Volume* 18, Issue 22, 2005, pp.4772-4784.

Jacobowitz, H., Stow, L.L., Ohring, G., Heidinger, A., Knapp, K. and Nalli, N. 2003: The Advanced Very High Resolution Radiometer PATHFINDER Atmosphere (PATMOS) climate data set: A Resource for Climate Research. *Bull. Amer. Meteor. Soc.,* June, 785-793.

James, M.E. and Kalluri, S.N., 1994: The Pathfinder AVHRR land data set: An improved coarse resolution data set for terrestrial monitoring. *Int. J. Remote Sens.* 15**,** 3347-3363.

Kidwell, K. B. (Ed), 1995, NOAA Polar Orbiter Data Users Guide. National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Services, National Climatic Data Center. Camp Springs MD, USA.

Kidwell, K. B. (Ed), 1997, Global Vegetation Index User's Guide. National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Services, National Climatic Data Center. Camp Springs MD, USA.

Kogan, F.N., 1997, Global Drought Watch from Space. *Bull. Amer. Meteor. Soc.,* 78, 621-636.

Kogan, F. N. Sullivan, J.T. and Pu Bu Ciren, 1996. Testing post-launch calibration for the AVHRR sensor on world desert targets during 1985-1993. *Adv. Space Res., vol 17*, No 1, 47-50.

Kogan, F.N., 1995: Droughts of the Late 1980s in the United States as Derived from NOAA Polar Orbiting Satellite Data. *Bull. Amer. Meteor. Soc*. 76, 655-668.

Kogan, F.N., J. Sullivan, R. Carey and D.Tarpley, 1994: Post-Pinatubo Vegetation Index in Central Africa. *Geocarto Int.,* 3: 51-58

Kogan, F., M. Goldberg, T. Schott, T., and W. Guo, 2015: Suomi NPP/VIIRS: improving drought watch, crop loss prediction, and food security. *Int. J. Remote Sens.,* 36(21): 5373-5383.

Kogan, F., W. Guo, and W. Yang, 2017: SNPP/VIIRS vegetation health to access 500 California drought. *Geomat. Nat. Hazards & Risk*, doi:10.1080/19475705.2017.1337654.

Kogan, F. Remote Sensing for Food Security; Springer International Publishing: Berlin/Heidelberg, Germany, 2019.

Kogan, F. Remote Sensing for Malaria: Monitoring and Predicting Malaria from Operational Satellites; Springer International Publishing: Berlin/Heidelberg, Germany, 2020.

Liu, W.T. and F. Kogan (2002), Monitoring Brazilian soybean production using NOAA/AVHRR based vegetation condition indices. *Int. J. Remote Sens*., 23(6), 1161–1179.

Rao, C. R. N. and Chen, J., 1993, Calibration of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) after launch. *Proceedings the Int. Soc. Optical Eng*., Orlando, Florida, 56-66.

Rao, C. R. N. and Chen, J., 1999, Revised post-launch calibration of the visible and near-infrared channels of the Advanced Very High Resolution Radiometer on the NOAA-14 spacecraft. *Int. J. of Remote Sensing*, 20, pp. 3485.Salazar, L., Kogan, F. and L. Roytman (2007), Use of remote sensing data for estimation of winter wheat yield in the United States. *Int. J. Remote Sens*., 28(17), 3795-3811.

Tarpley, J.P., Schneider, S.R. and Money, R.L. 1984: Global vegetation index from NOAA-7 meteorological satellite. *J. Climate & Appl. Meteor.*, 23, 491-494.

Vargas, M., Kogan, F and Guo, W. 2009: Empirical normalization for the effect of volcanic stratospheric aerosols on AVHRR NDVI. *Geophys. Res. Lett., vol 36*.

Tucker, C.J., Pinzon, J.E., Brown, M.B., Slayback, D.A., Pak, E.W., Mahoney, R., Vermote, E.F. and El Salcous, N. 2004: An extanded AVHRR 8-km NDVI data set compatible with MODIS and SPOT vegetation NDVI data. *Int. J. Remote Sens.*.

Yang, W., W. Guo, and F. Kogan. 2018. VIIRS-based High Resolution Spectral Vegetation Indices for Quantitative Assessment of Vegetation Health: Second Version. *Int. J. Remote Sens.* 39 (21): 7417-7436.

Yang, W., F. Kogan, and W. Guo. 2020. An Ongoing Blended Long-Term Vegetation Health Product for Monitoring Global Food Security. *Agronomy* 10 (12): 1936. doi:10.3390/agronomy10121936.

Yang, W., F. Kogan, W. Guo and Y. Chen. 2021 A novel recompositing approach to create continuous and consistent cross-sensor/cross-production global NDVI datasets, *Int. J. Remote Sens.*, 42:16, 6025-6049, DOI:10.1080/01431161.2021.1934597.

END OF DOCUMENT