The Dynamic Response of Terrestrial Vegetation to Climate Variability Seen Through Time Series Analysis of Satellite Data

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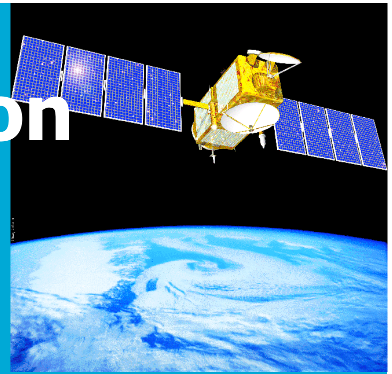
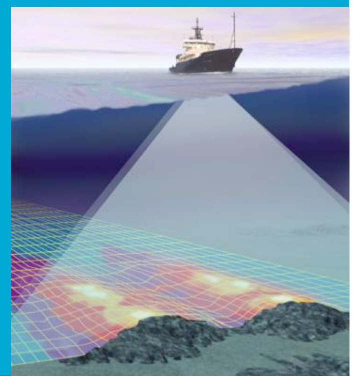


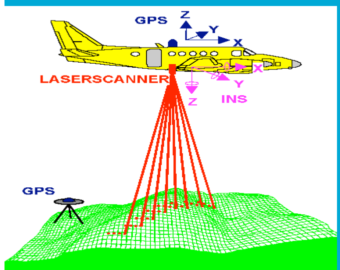
space born

- Positioning
- Gravity Field
- Remote Sensing
  - Optical
  - Radar
  - Acoustic
- Geophysical modeling

in situ

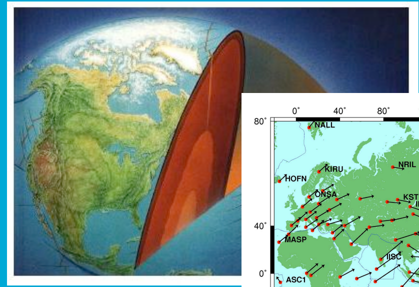


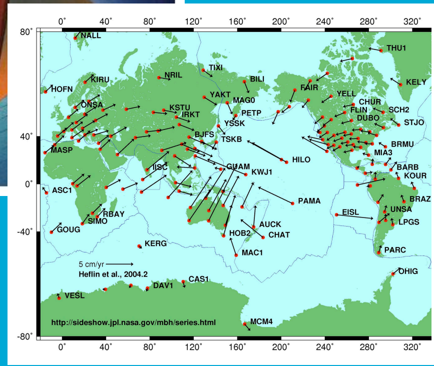
airborne

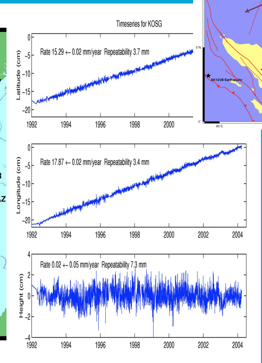


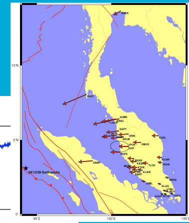
GEOPHYSICAL SIGNALS:

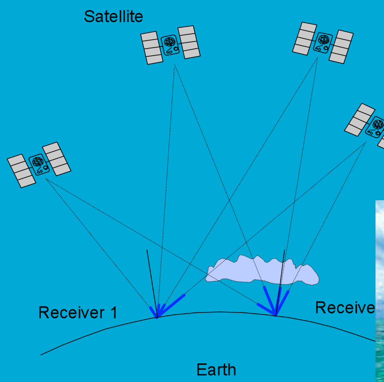
- Solid Earth
- Hydrosphere
- Atmosphere
- Terrestrial biosphere

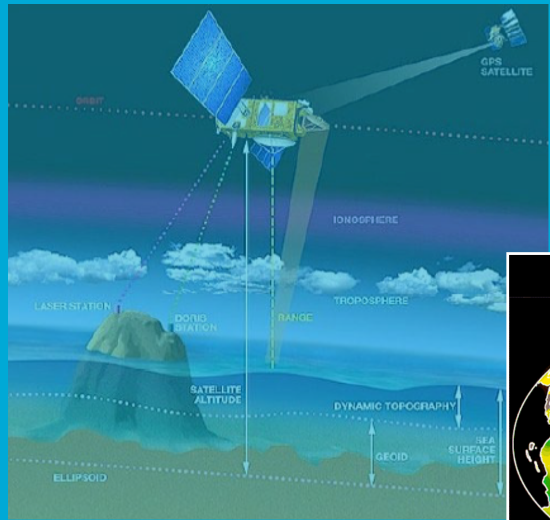


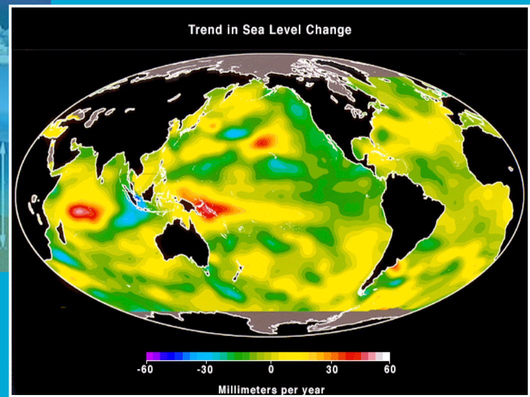


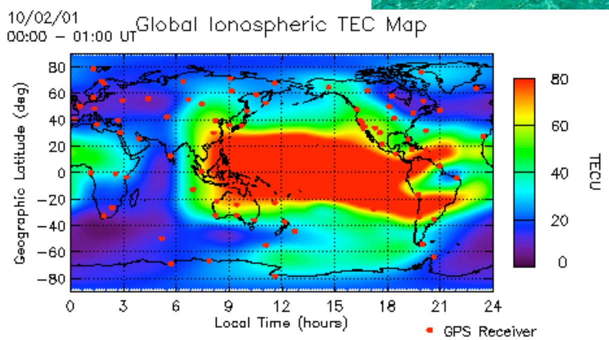






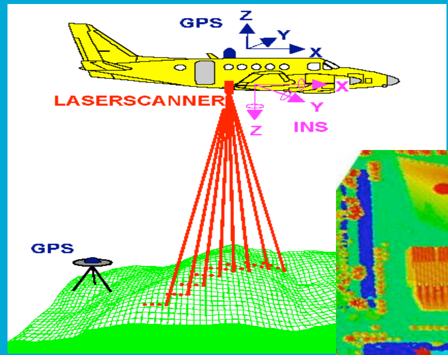


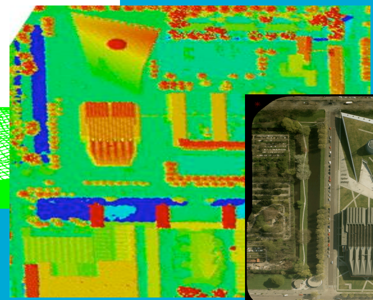


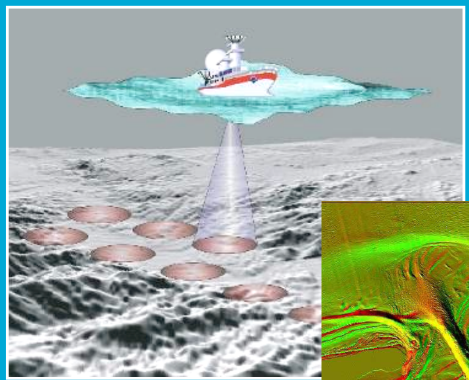


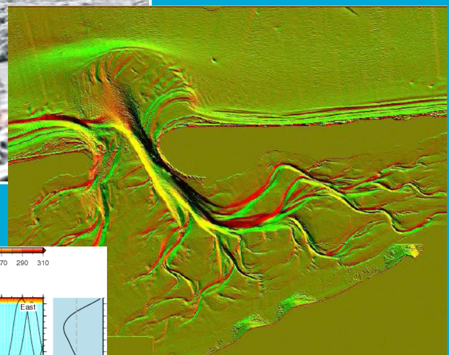
REMOTE SENSING:

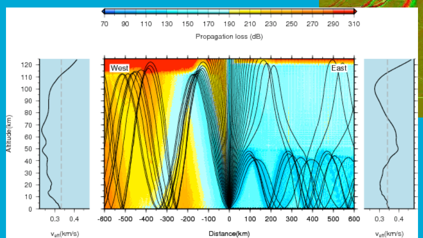
- Optical RS
- Acoustic RS
- Radar RS

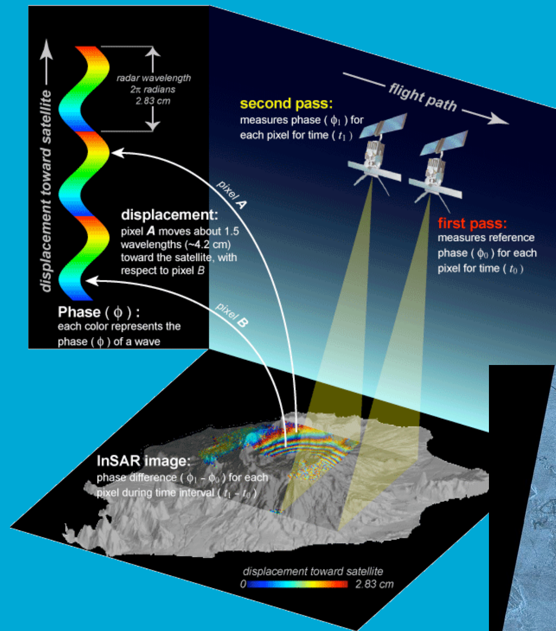


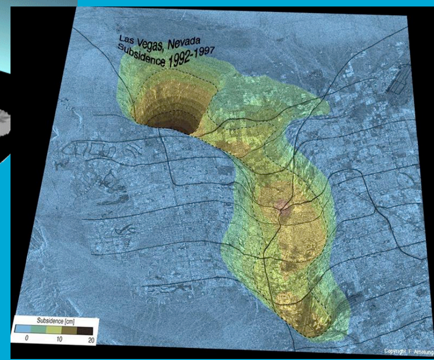




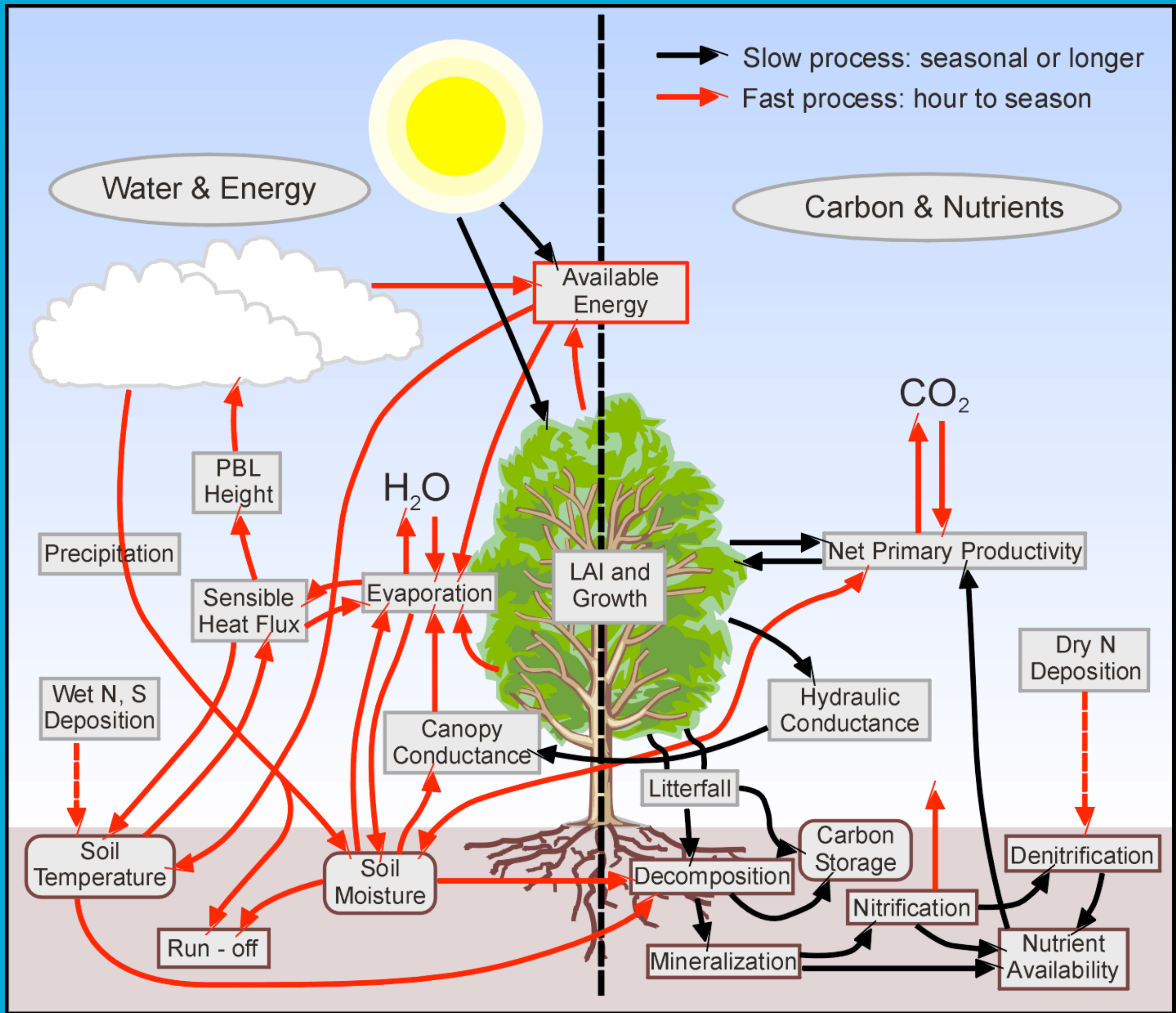








What determines the response of vegetation to weather and climate?



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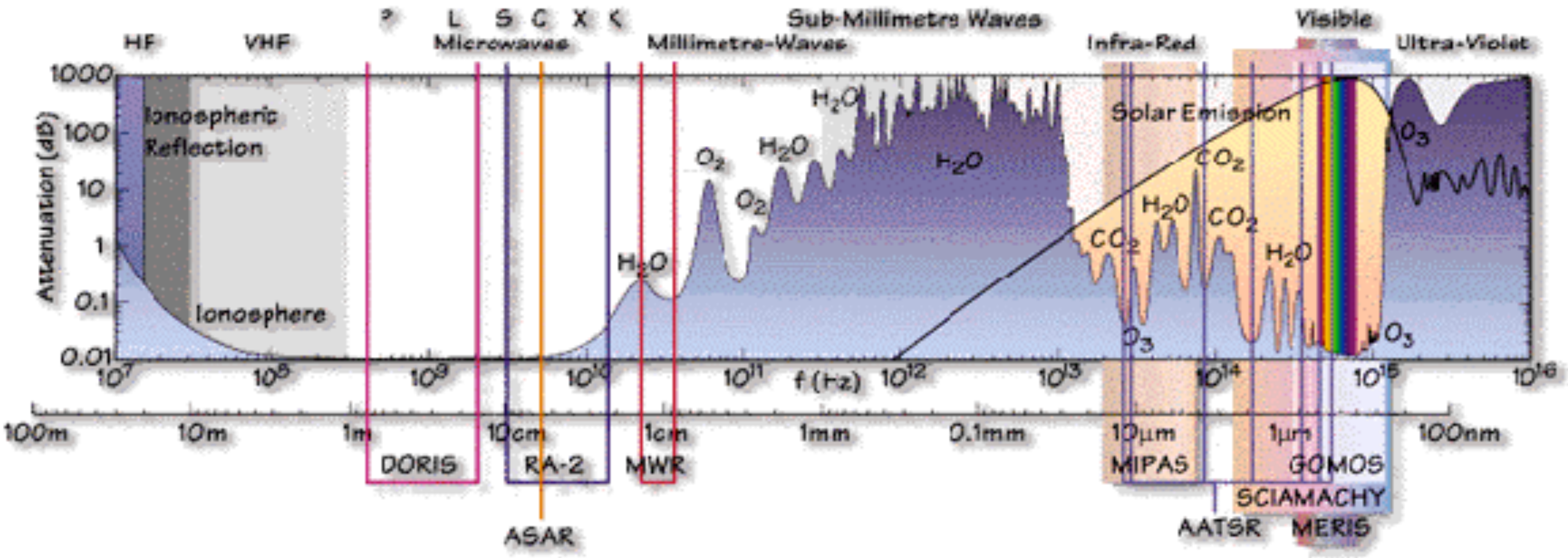
Observing land surface from space

1. Can we use radiometric data to understand terrestrial vegetation?

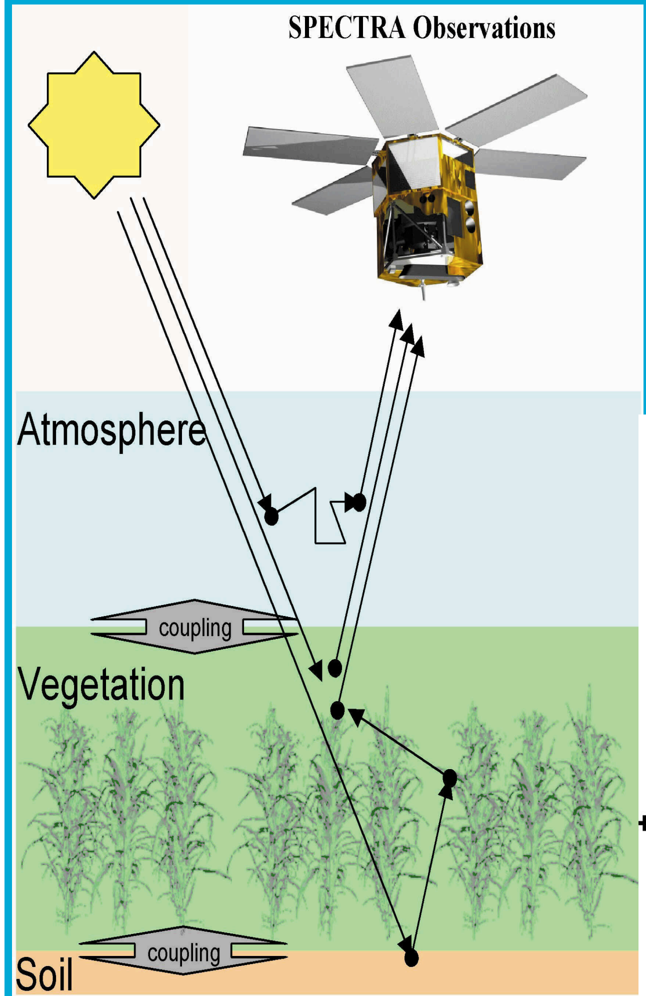
2. How complex is EM signal over vegetation?

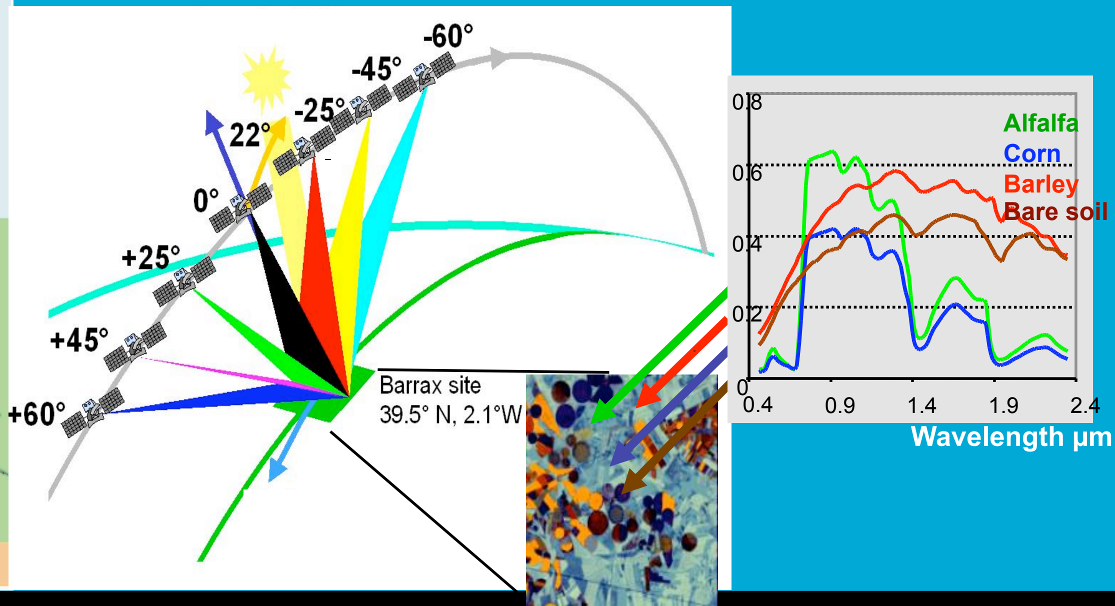


Observation Technique

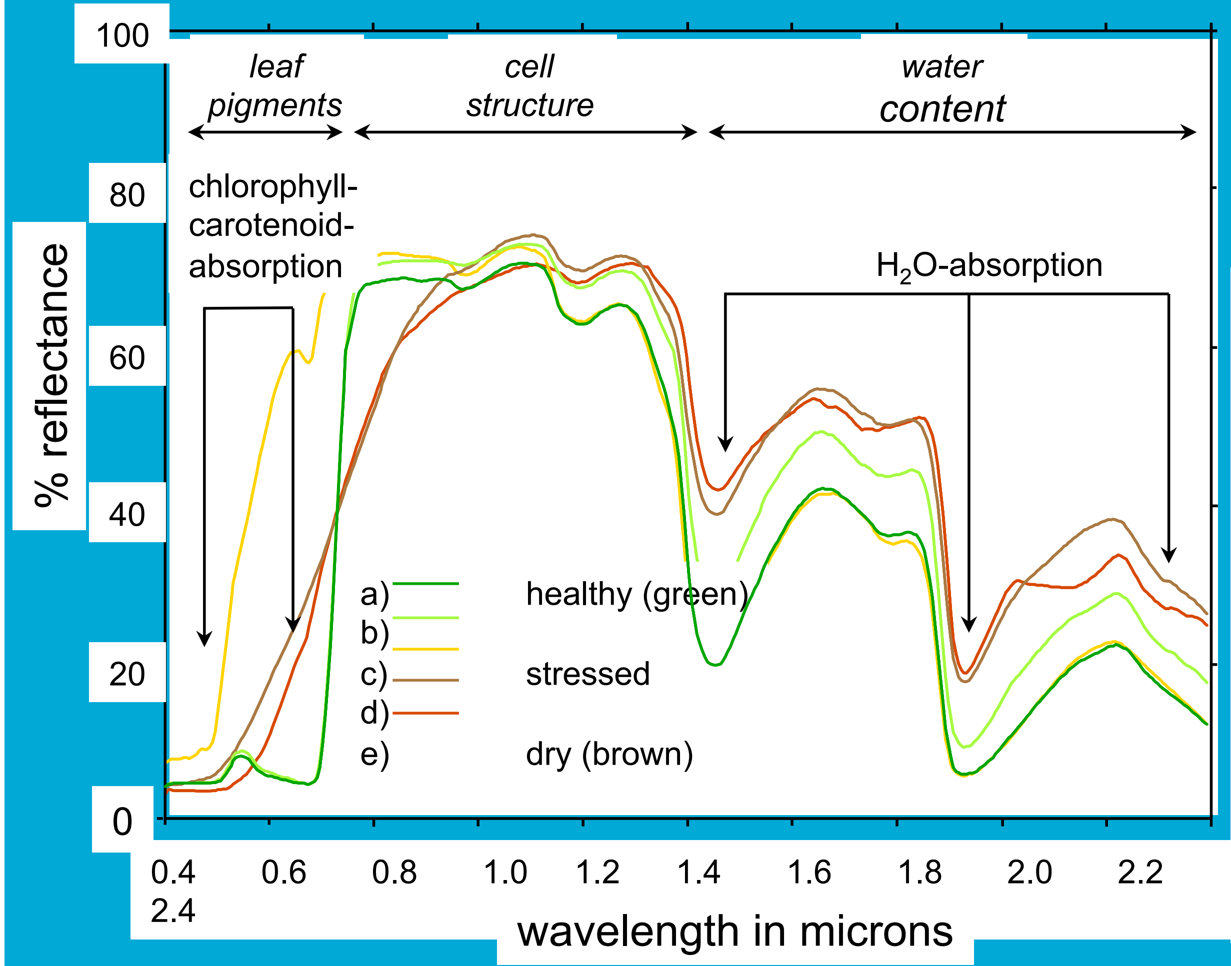
- Top of the atmosphere (TOA) radiance over terrestrial vegetation determined by complex interactions at the surface and in the atmosphere.

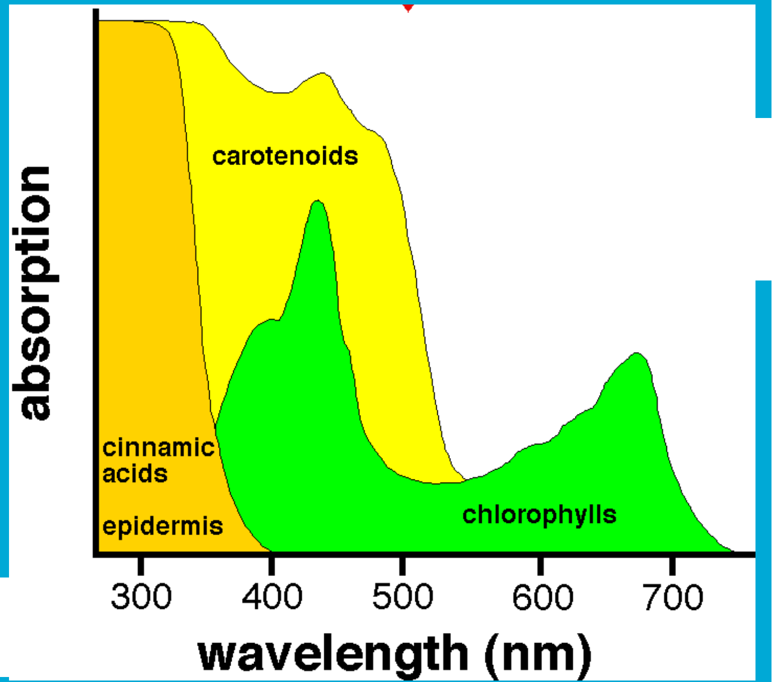
- Sampling the spectral, directional, spatial, and temporal dimensions of radiometric magnitudes is needed to decouple both the surface and the atmosphere and characterise them separately.





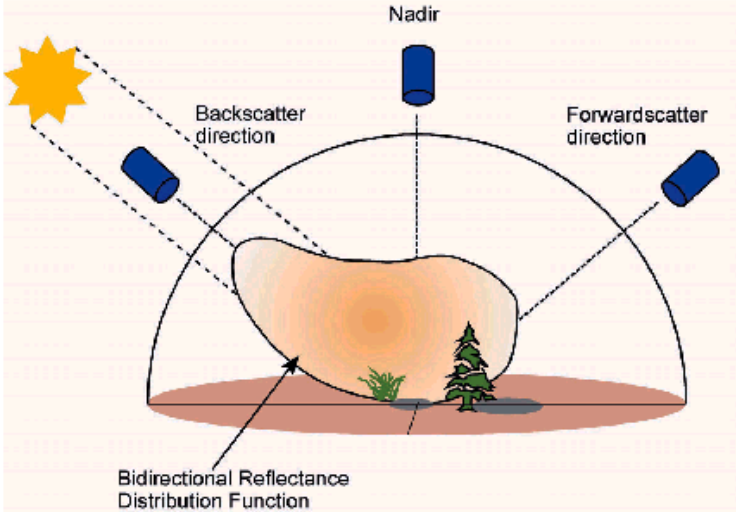
Spectral Characteristics VIS/NIR/SWIR

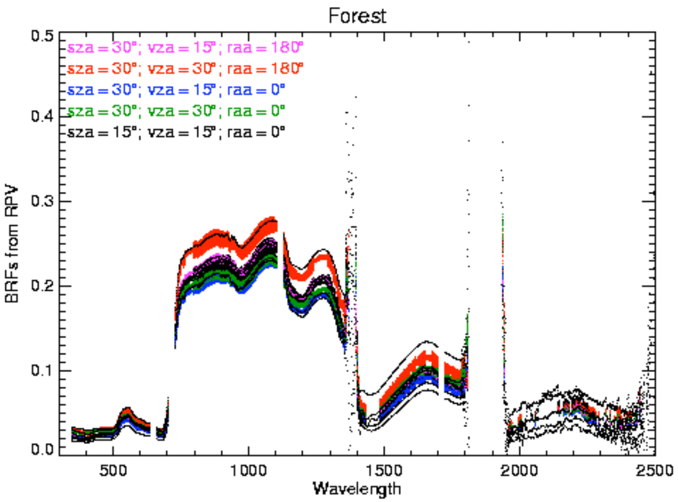




Leaf biochemical composition determines spectral reflectance and changes

Anisotropy of reflectance





The hemispherical reflectance $\alpha_0(\lambda)$ is related to radiances and to the bi-directional reflectance of the surface as:

$$\alpha_0 = \int_0^{2\pi}\int_0^{1}\Big(\int_0^{2\pi}\int_0^{1} r(\mu,\phi;\mu',\phi')\,\mu_0 F_0 T(\mu',\phi';\mu_0,\phi_0)\,\mu' d\mu' d\phi' + r(\mu,\phi;\mu_0,\phi_0)\,\overline{\mu_0}\, F_0 \exp\!\Big(-\frac{\tau_1}{\mu_0}\Big)\Big) d\mu d\phi \,\Big[\int_0^{2\pi}\int_0^{1}\Big(T(\mu,\phi;\mu_0,\phi_0) + \exp\!\Big(-\frac{\tau_1}{\mu_0}\Big)\Big)\,\mu_0 F_0\, \mu d\mu d\phi\Big]^{-1}$$

where:

$r(\mu,\varphi;\mu',\varphi')$	=	reflectance of radiance of direction μ',φ' in the direction μ,φ
μ	=	$\cos\Phi$, Φ = zenith angle
μ_0	=	$\cos\Phi_{sun}$
φ	=	azimuth angle
F_0	=	solar radiance outside the atmosphere
$T(\mu',\varphi';\mu_0,\varphi_0)$	=	transmission function
τ_1	=	optical depth of entire atmosphere

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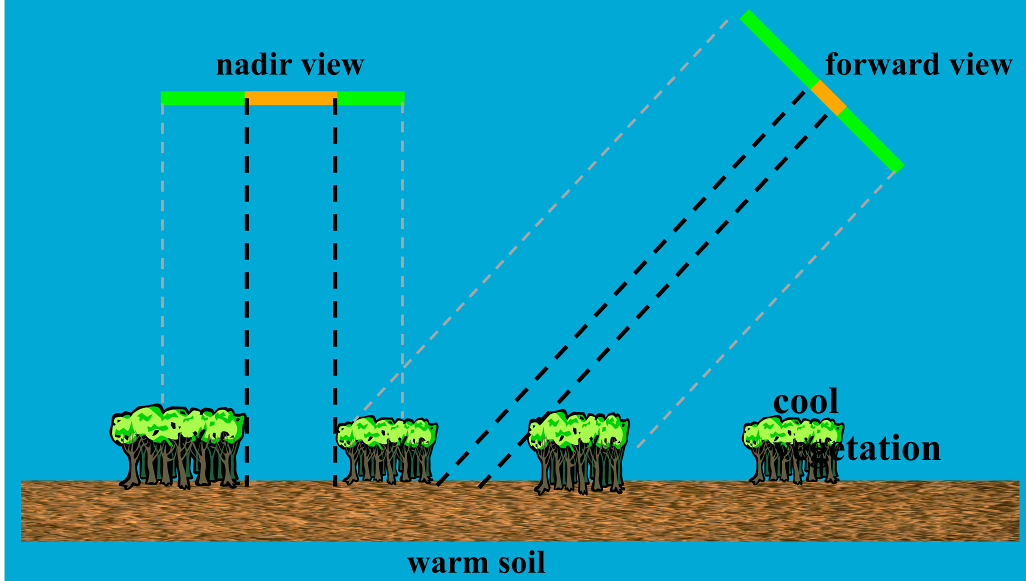
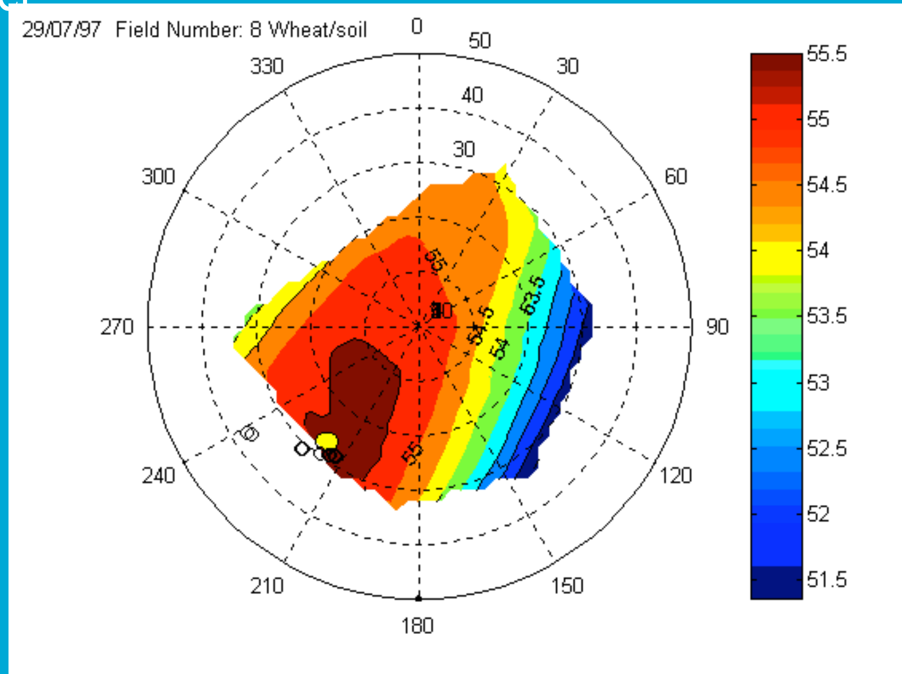
Thermal heterogeneity of vegetation canopies and heat transfer

Mixtures of foliage and soil = thermally heterogeneous
Radiometric temperature depends on view direction
Exitances of mixture elements can be added together



<u>T</u>emperature <u>D</u>irectional <u>D</u>istribution (TDD)



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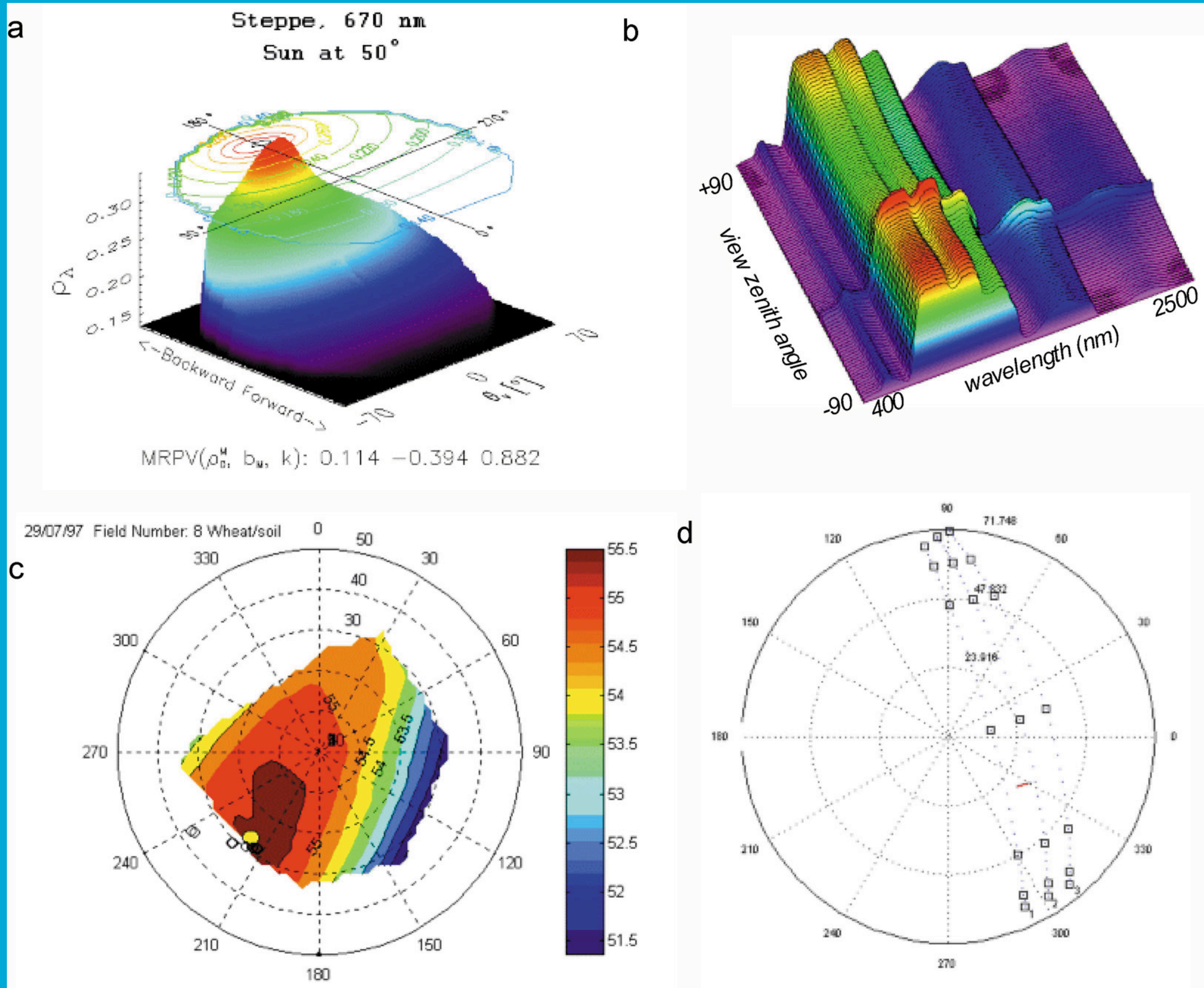
Sampling fundamental radiometric magnitudes

a. Bidirectional Reflectance Factor (BRF)

b. Hyperspectral reflectance vs. view angle

c. Bidirectional Temperature Distribution Function (BRTF)

d. Along track angular sampling



Angular samples must be nearly simultaneous = Along Track Observations

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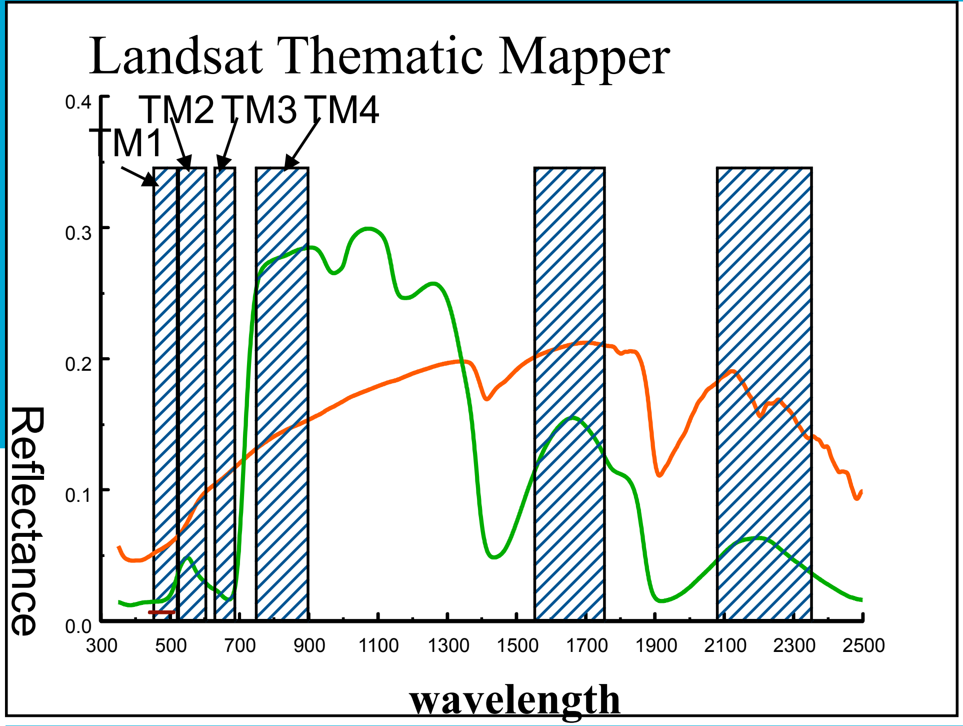
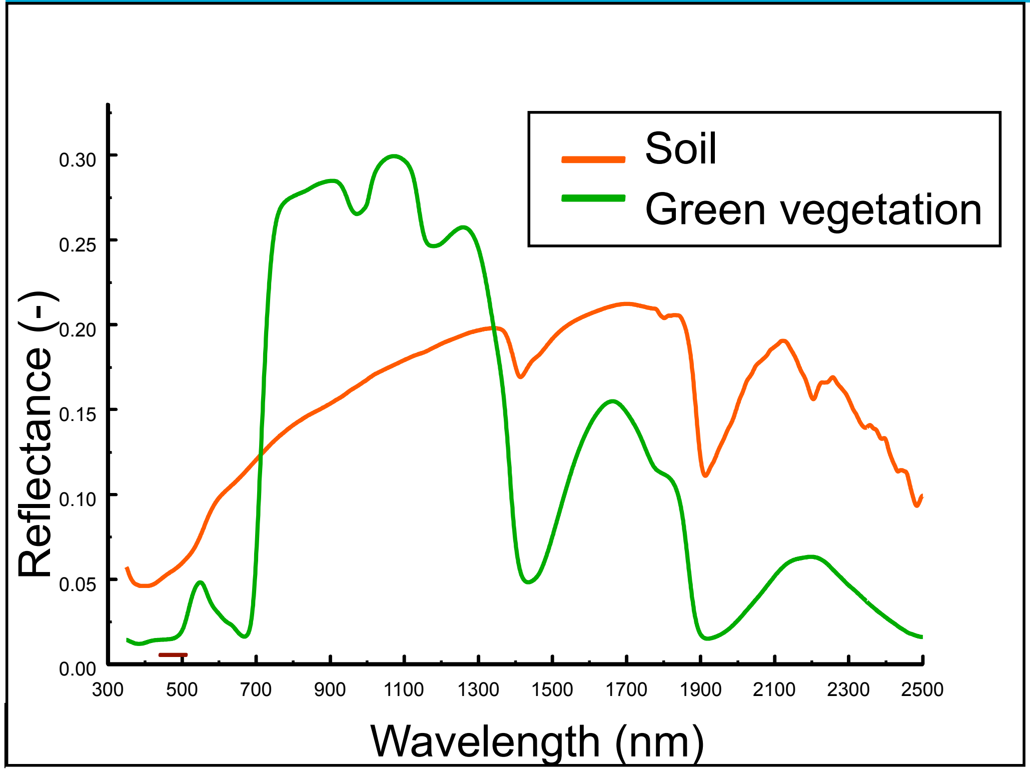
The simplest observation of terrestrial vegetation

Normalized Difference Vegetation Index =

(TM4 – TM3) / (TM4+TM3)



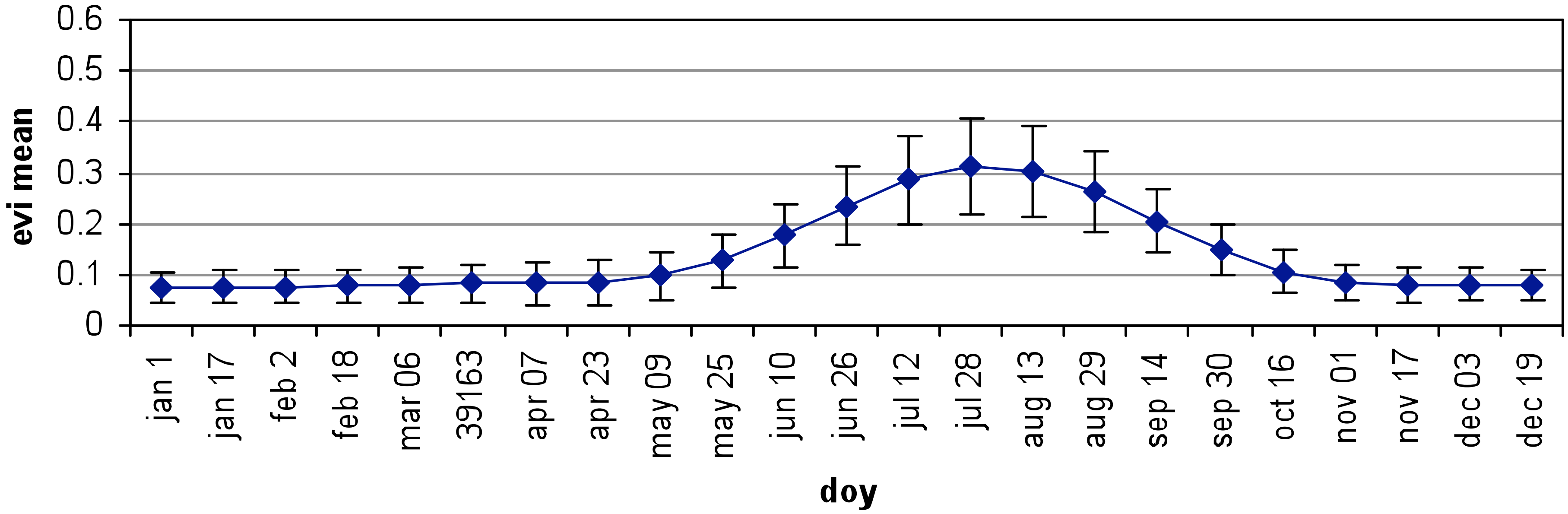


Biophysical observable:

Fraction Absorbed Photosynthetically Active Radiation

$fAPAR = f(\rho_\lambda)$

Time series of VI = vegetation phenology



- **VI climatology = average phenology = vegetation type**
- **Interannual VI variability = response of vegetation to climate variability**
- **Short term anomalies = response to weather (drought)**

Fourier analysis of time series of satellite data

When and how it began

- How to correct for time lag in local land surface temperature in large TIR images from geostationary satellites? Meteosat North Africa + Middle East 48 slots per day: 1987 - 88 Menenti and Verhoef
- Anomalies in crop phenology: AVHRR NDVI Zambia: 1989 - 90 Menenti et al.
- Many applications followed (see next slide)
- Number of published papers per year is increasing: several scientists have picked up the idea and new algorithms (e.g. wavelets)
- Applications range from classifications of biomes, to the determination of the length of growing season to the observation of vegetation response to climate variability to monitoring of ET

Drought, phenology, NDVI (t) and fAPAR(t)

drought = Budyko aridity index = net radiation / precipitation

vegetation phenology = Fourier transform of NDVI (t)

NDVI (t) AVHRR
Africa = monthly composites 7.6 x 7.6 km aug 1981 - dec 1992
South America = same jan 1982 - jun 1992
Europe = 10 days composites 1 x 1 km 1990, 1991, 1995, 1996, 1997
W-Argentina = monthly composites 7.6 x 7.6 km Jul 1982 Jun 1991

fAPAR (t) MODIS

Tibet = 8 days composites 1 km x 1 km jan 2000 – sept 2006

Sichuan = 8 days composites 1 km x 1 km jan 2000 – dec 2006

HANTS algorithm

- Harmonic ANalysis of Time Series
- Generalisation of MVC (maximum value compositing)
- Curve fitting using sine and cosine basis functions
- Amplitude and phase parameters contain concise information on response of vegetation
- Iterative process of outlier removal
- Largest negative outliers are removed first
- Process stops if:
  1) error of fit < threshold
  2) number of remaining points becomes too small
- Output: mean values plus amplitudes and phases of all low-frequency harmonics (user-defined)

Benefits

- Data reduction
- Cloud removal
- Synthesis of smoothed time series of images

Harmonic model of time series

$$y(t) = a_0 + \sum_{i=1}^{n} a_i \cos(\omega_i t - \varphi_i)$$

a = amplitude

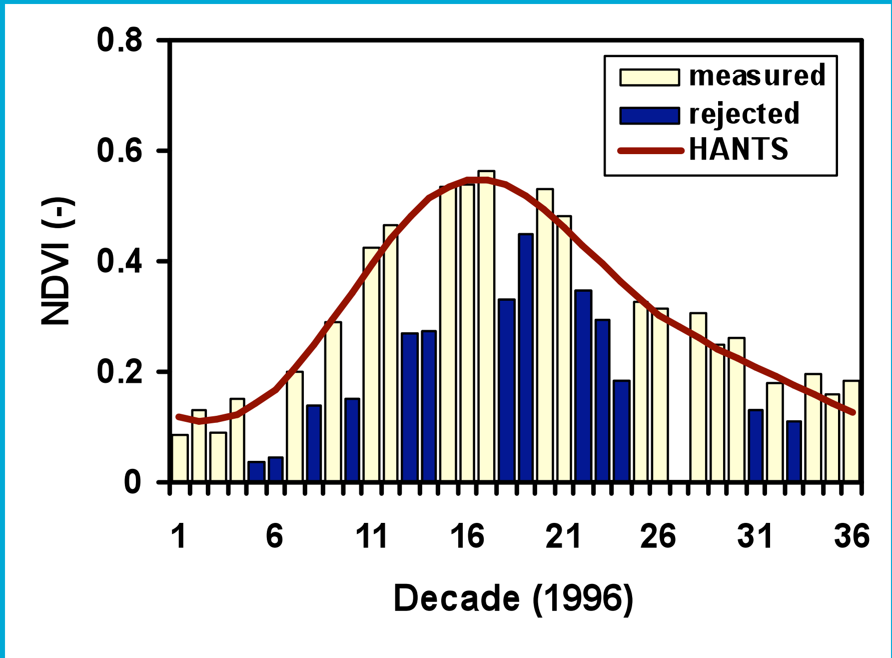
ω = frequency $\times 2\pi$

φ = phase

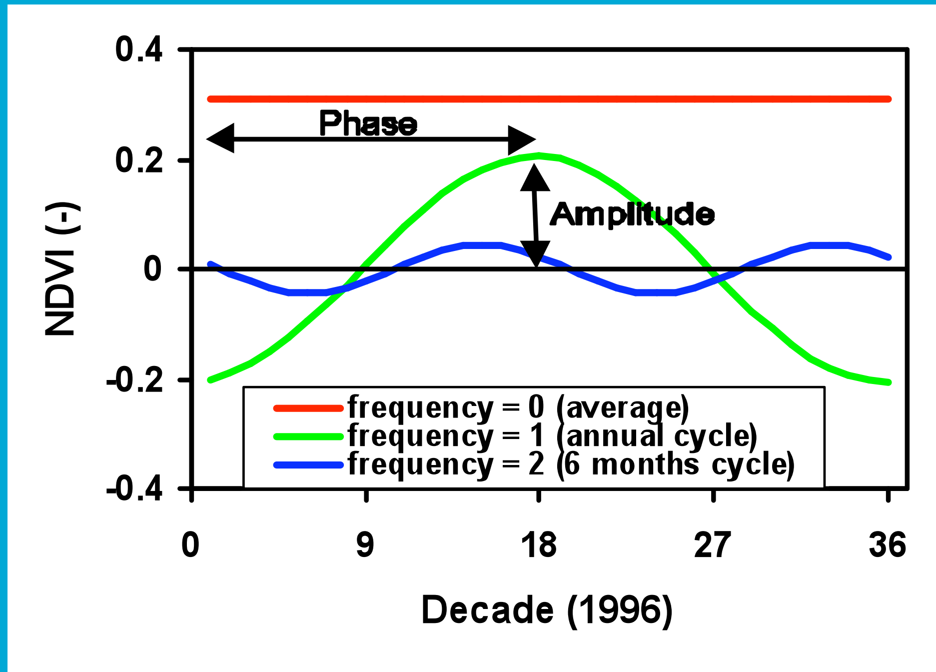
How does HANTS work?

•Time average, yearly and 6 months amplitude + phase used to reconstruct observations

•outliers detected and eliminated



bars = observations

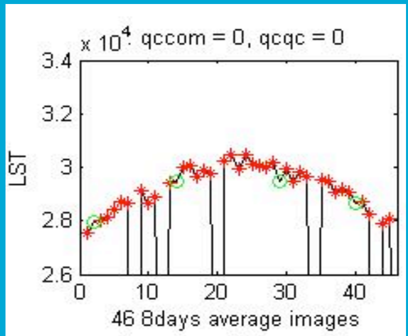


dominant coefficients

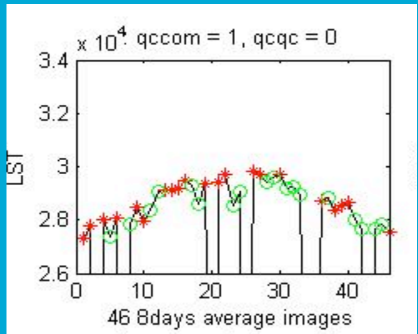
Cloud-free time series construction

Defining a quality check (QC) indicator of the satellite time series data by some criteria:

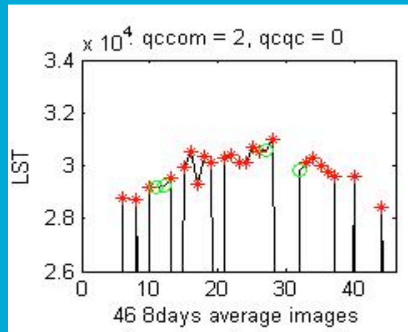
- **Ratio of missing to potential observations;**
- **Largest continuous gap in the observations;**
- **Number of gaps;**
- **Retrieval quality of land surface parameters.**



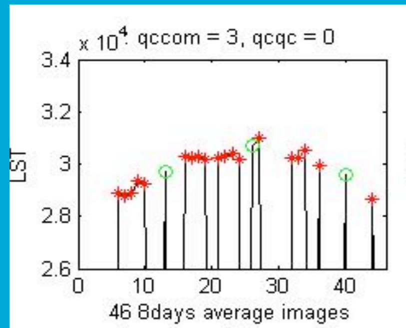
Best **QC = 0**



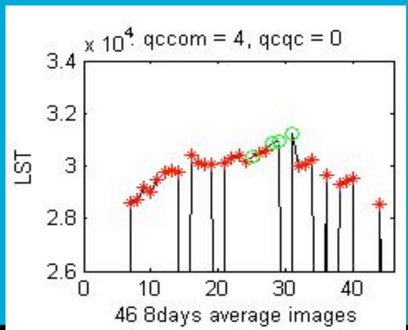
QC = 1



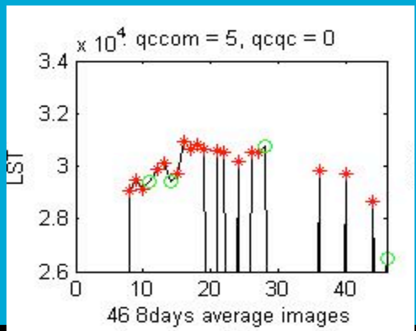
QC = 2



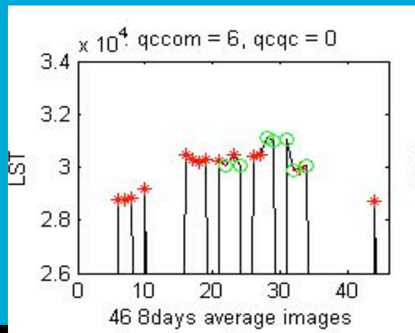
QC = 3



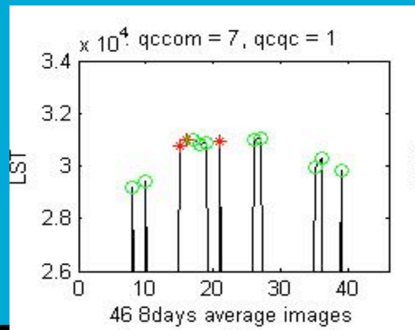
QC = 4



QC = 5



QC = 6

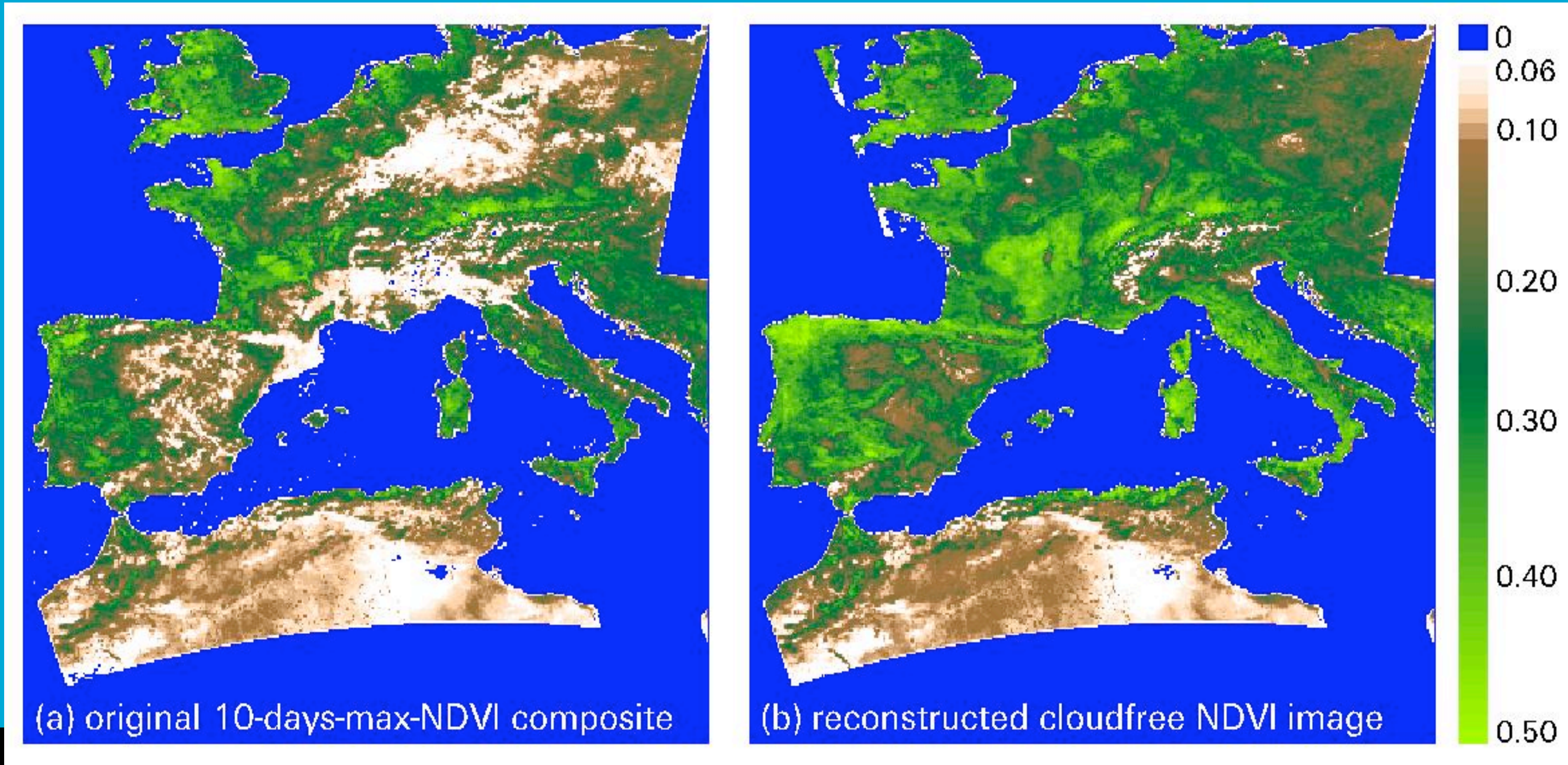


QC = 7 Worst

Cloud screening and modeling of time series

•Clouds elimination - HANTS

•interpolation of land observations - HANTS



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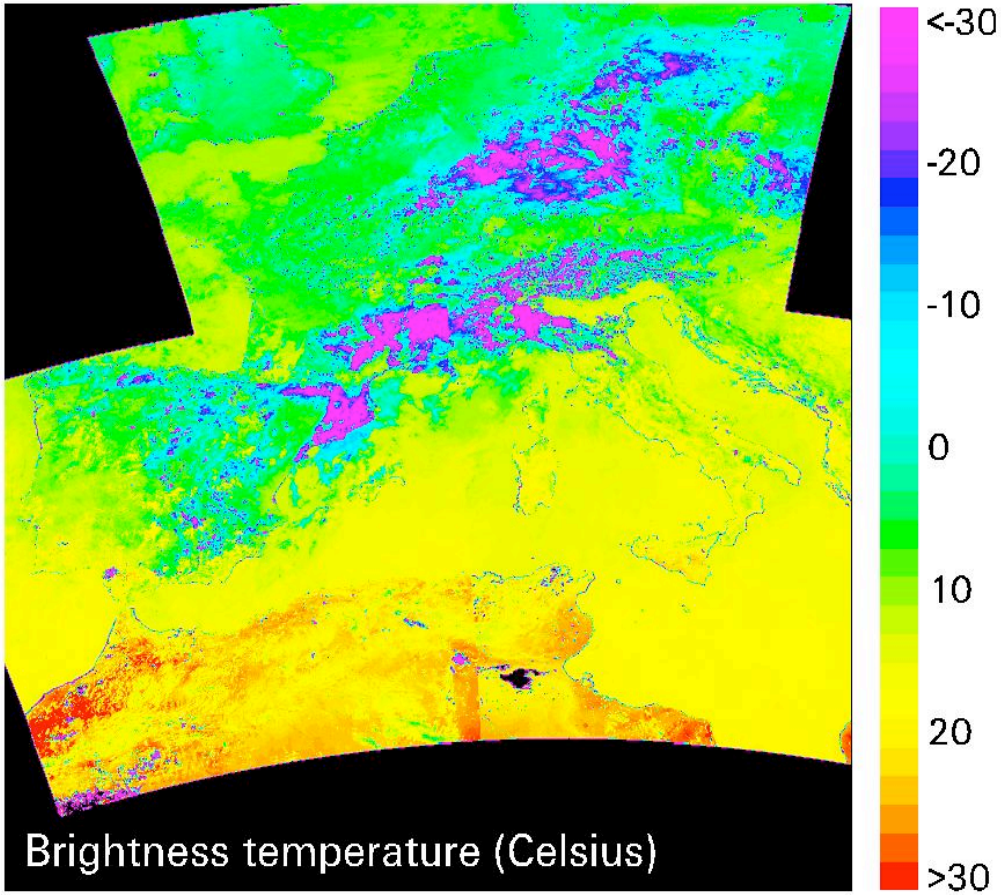
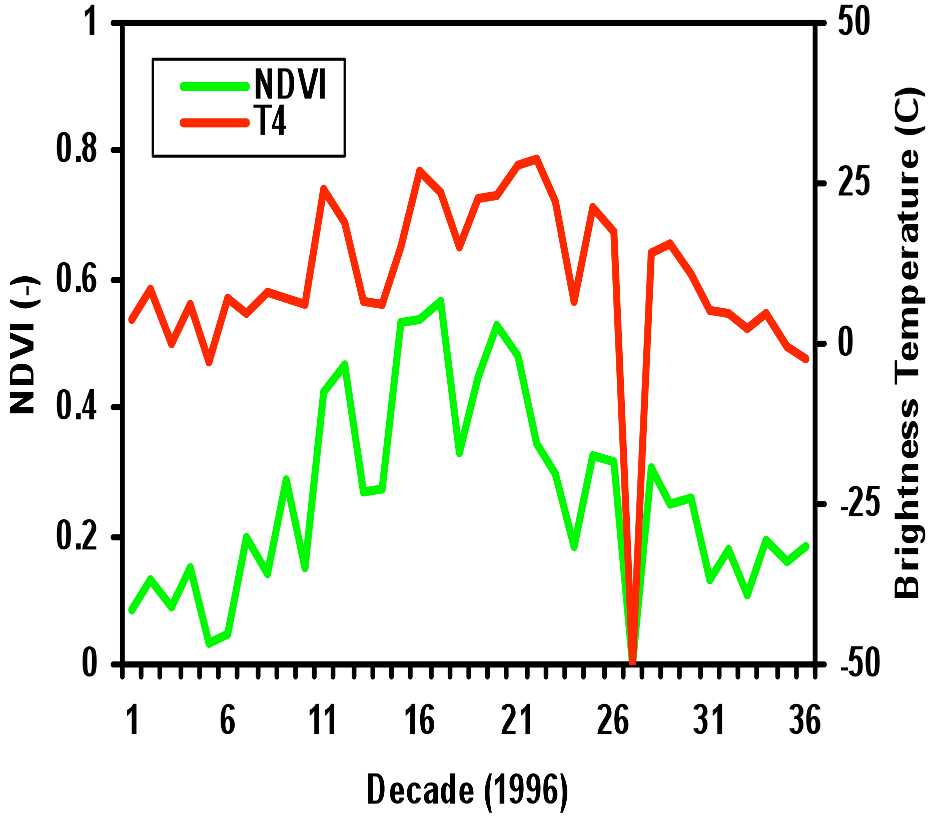
Cloud elimination: validation

•Clouds = low temperature



•Clouds = low NDVI AND low temperature



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Measure and Visualize Phenology:

Intensity Hue Saturation

transform of Fourier coefficients

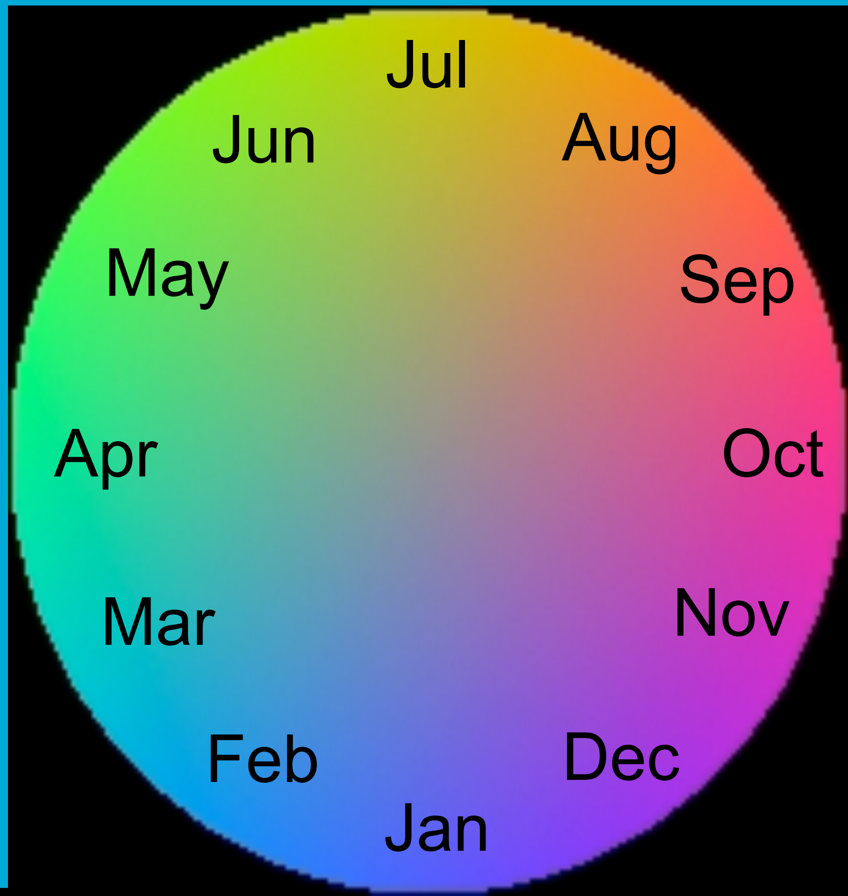
IHS-transform for colour compositing HANTS results

Colour indicates time of maximum NDVI during the year

$$r = M \times \left[1 + \frac{A}{A_{max}} \cos(P - 240°)\right]$$

$$g = M \times \left[1 + \frac{A}{A_{max}} \cos(P - 120°)\right]$$

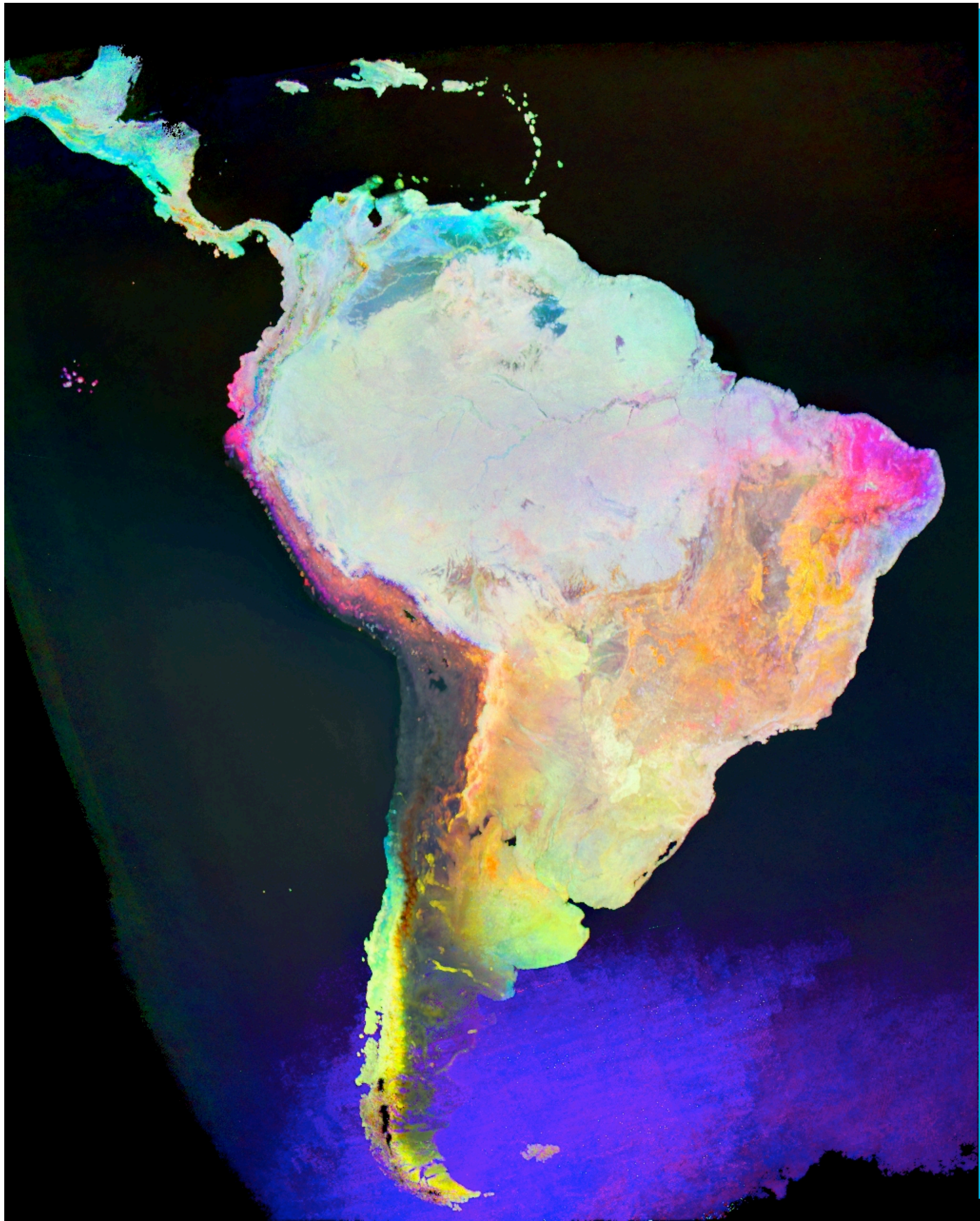
$$b = M \times \left[1 + \frac{A}{A_{max}} \cos P\right]$$



M = mean NDVI

A = amplitude

P = phase (deg)



South America

108 NOAA-AVHRR NDVI monthly composites of 1982-1991 (source NASA GSFC) processed by HANTS algorithm

IHS colour transformation:

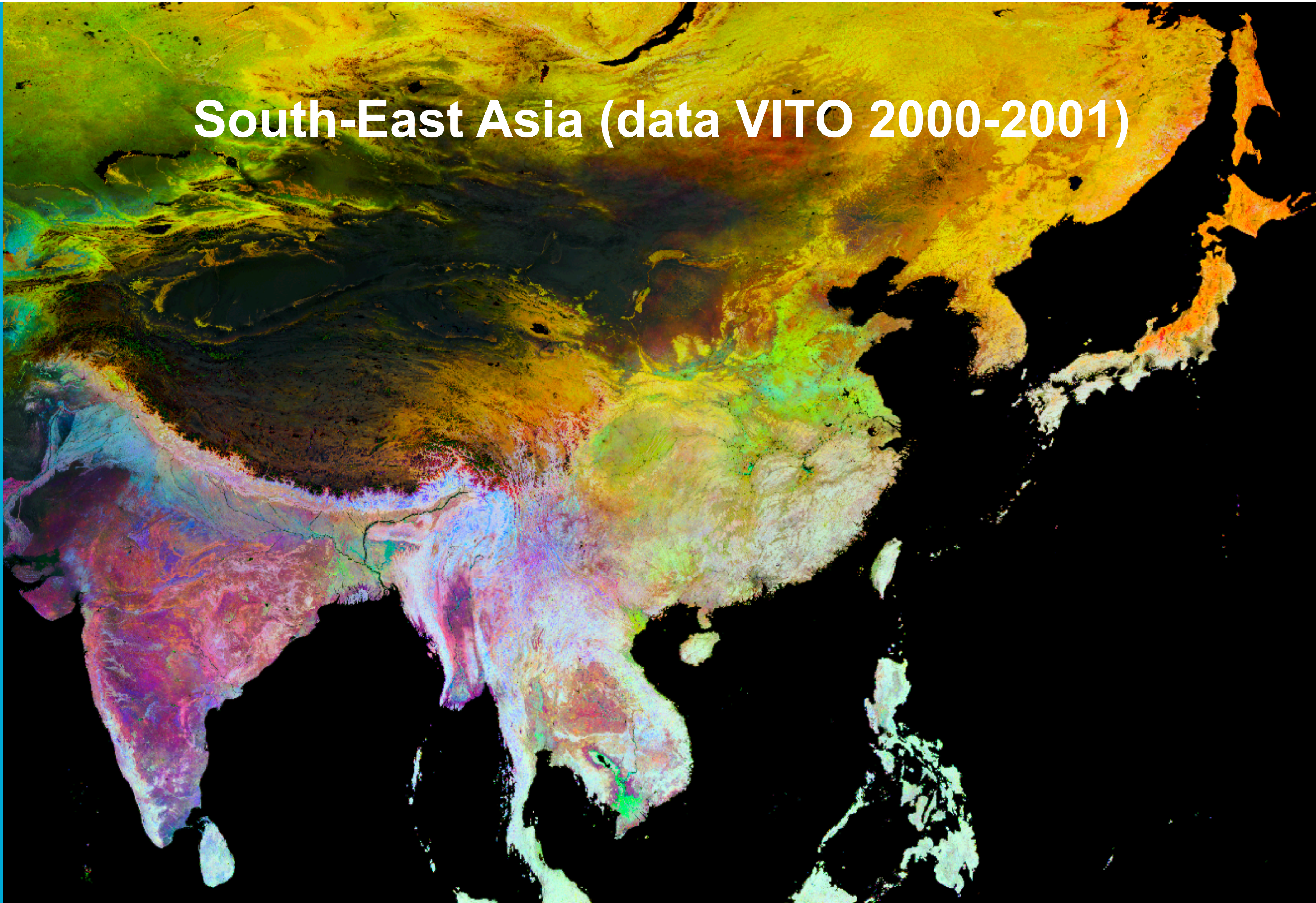
Annual mean => Intensity
Phase => Hue
Annual amplitude => Saturation

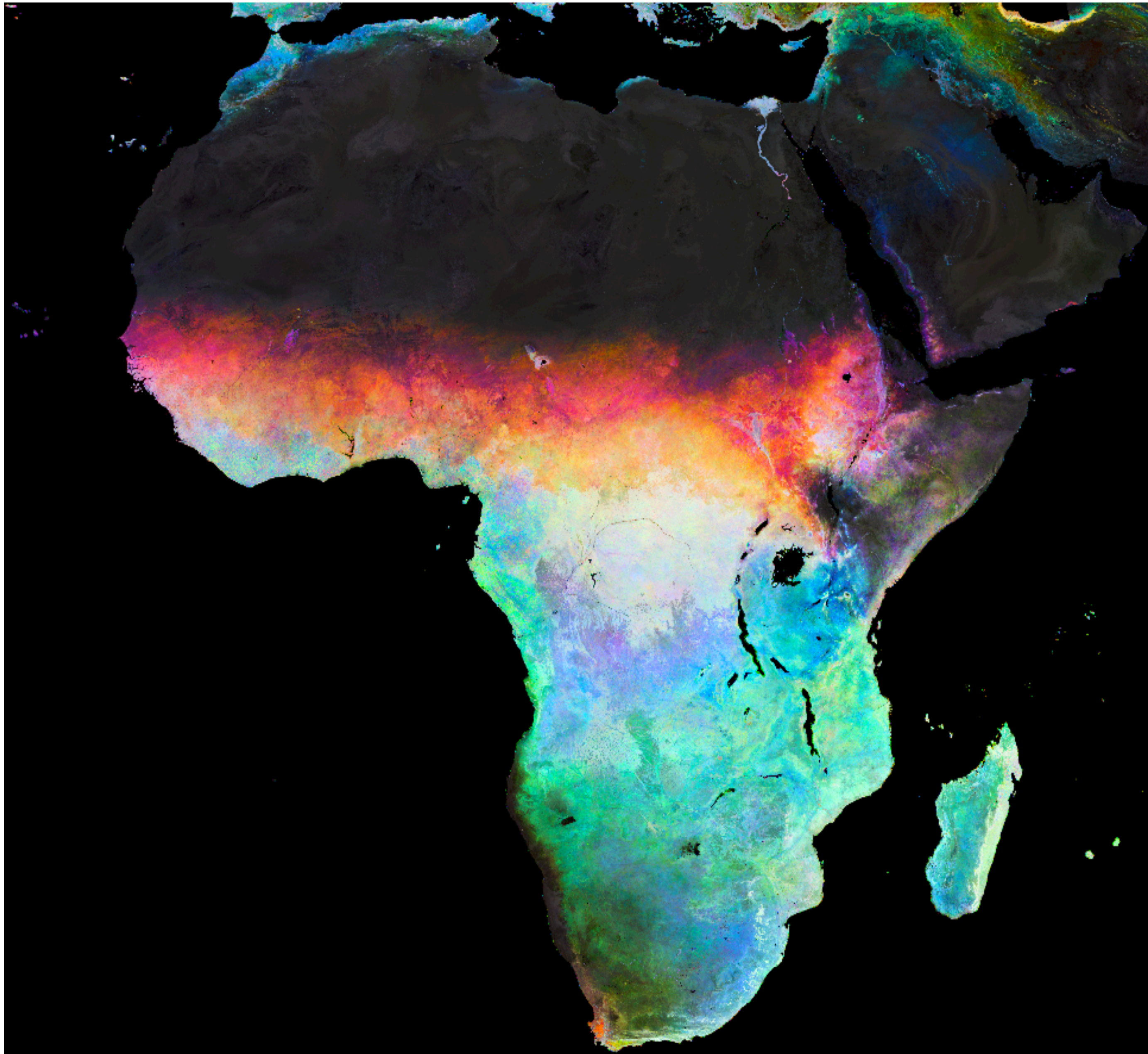
Phase of maximum NDVI <> Colour:

Jul	**Blue**
Sep	**Cyan**
Nov	**Green**
Jan	**Yellow**
Mar	**Red**
May	**Magenta**

Note the blue region. This is an artifact due to the "terminator effect", which gives artificially high NDVIs in the winter period

South-East Asia (data VITO 2000-2001)





Africa IHS SPOT-VEG image at ~10 km resolution (data 2000-2001 from VITO)

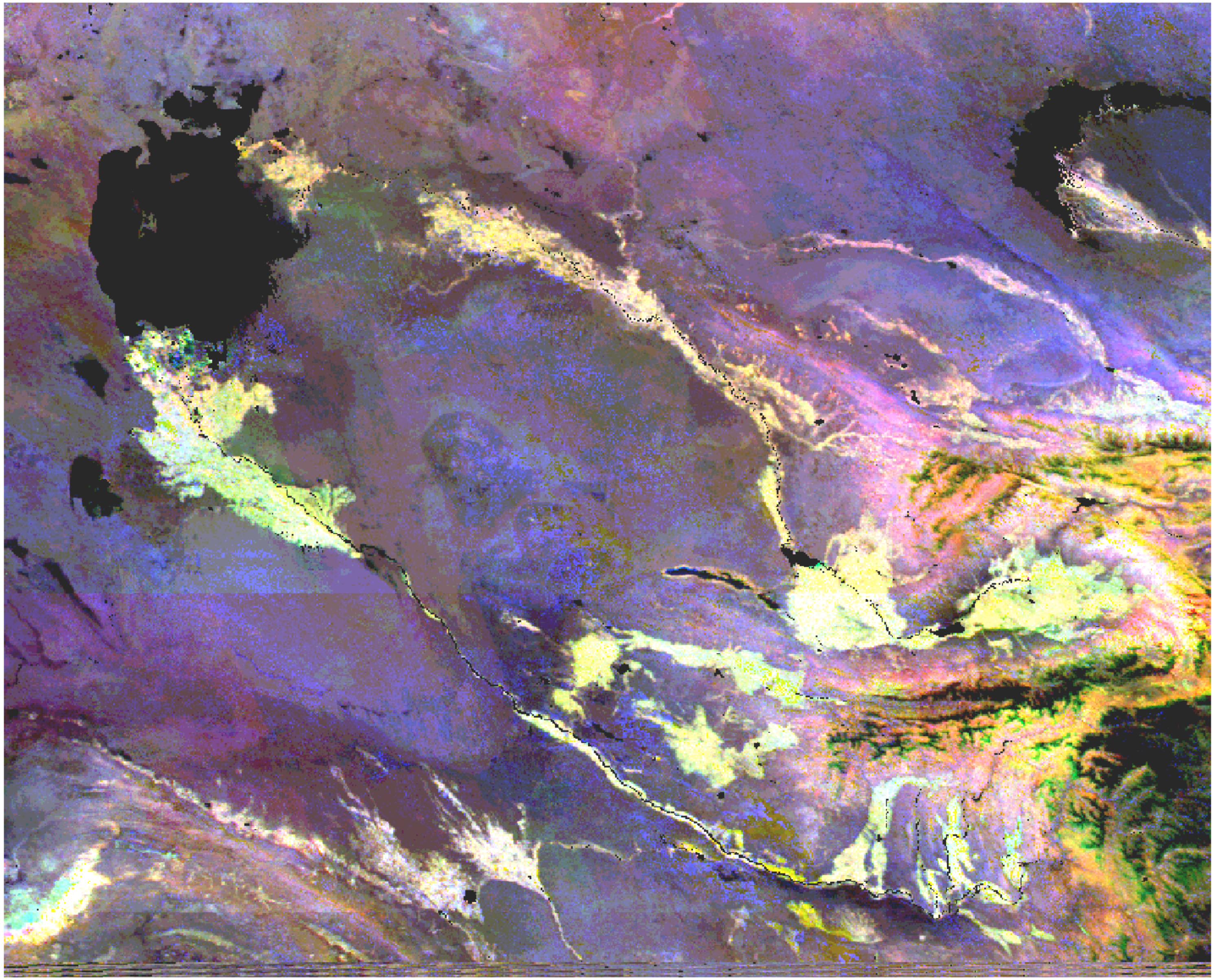
Classification of

Land Cover – Soil – Climate complexes

based on phenology

Aral Basin 1992

Colour composite of multitemporal images of the Soil Adjusted Vegetation Index (SAVI) calculated with AVHRR Ch1 and Ch2 reflectance at 1 km spatial resolution, Aral Sea Basin 1992: SAVI (April)= red; SAVI (june)= green; SAVI (august)= blue; area is 1568 km x 1232 km; greenish areas = irrigated lands

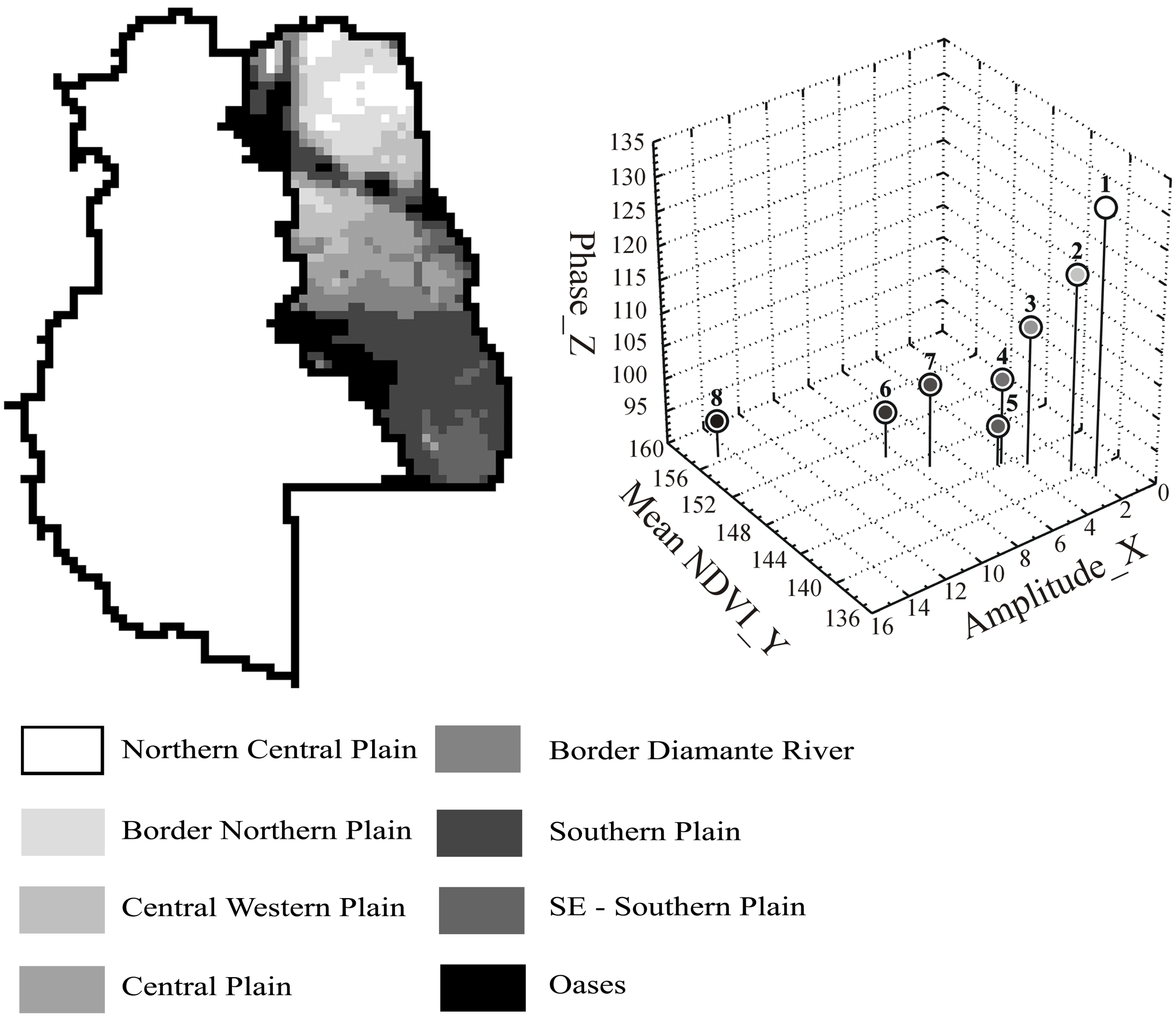


Western Argentina

July 1982 – June 1991

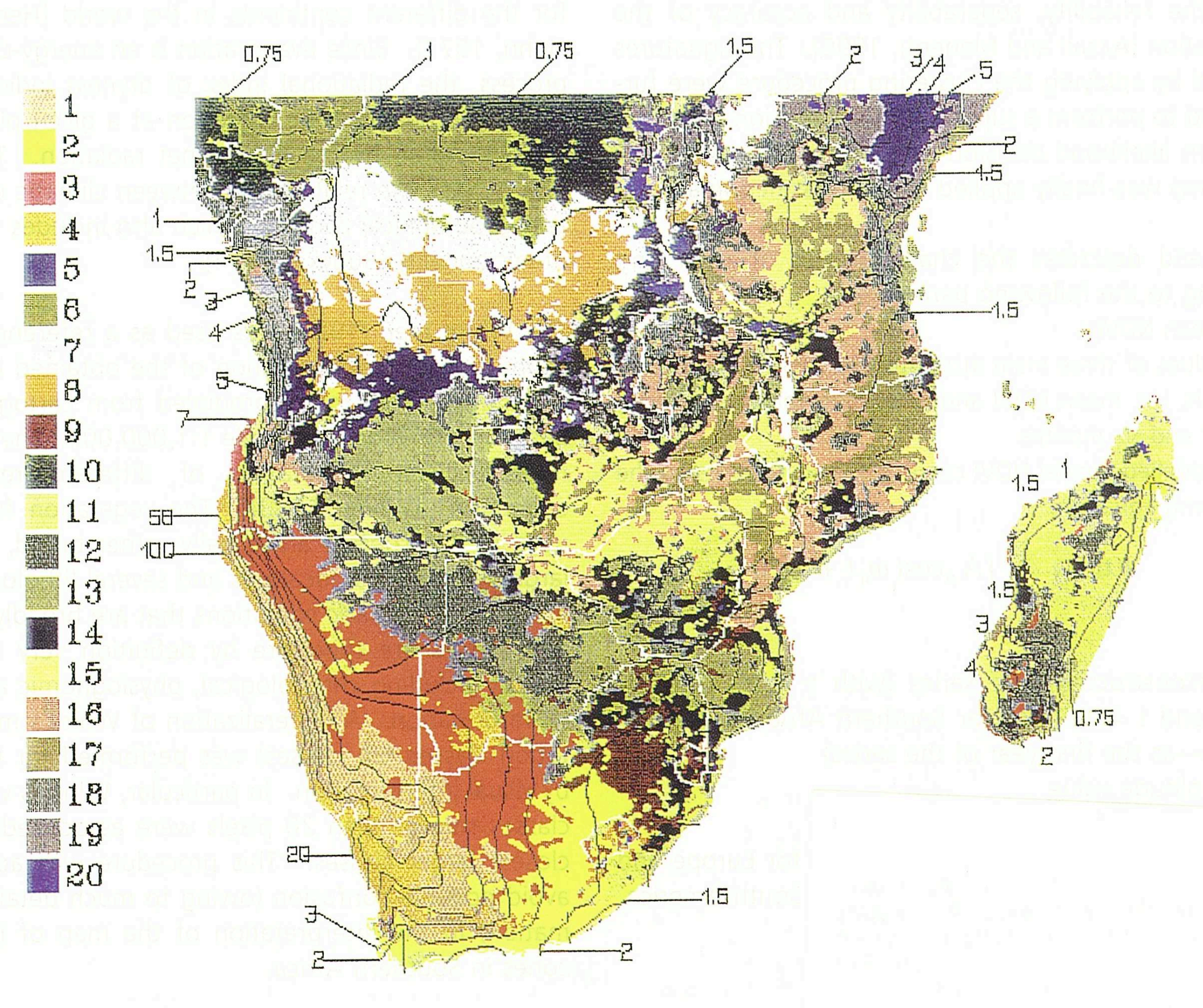
Loyarte et al. , 2008

(a) Map of foliar isophenology *(b)* 3D Scatterplot of class mean values



Southern Africa 1981 – 1992

Azzali and Menenti, 2000



Southern Africa

-AVHRR NDVI

-1981 1992

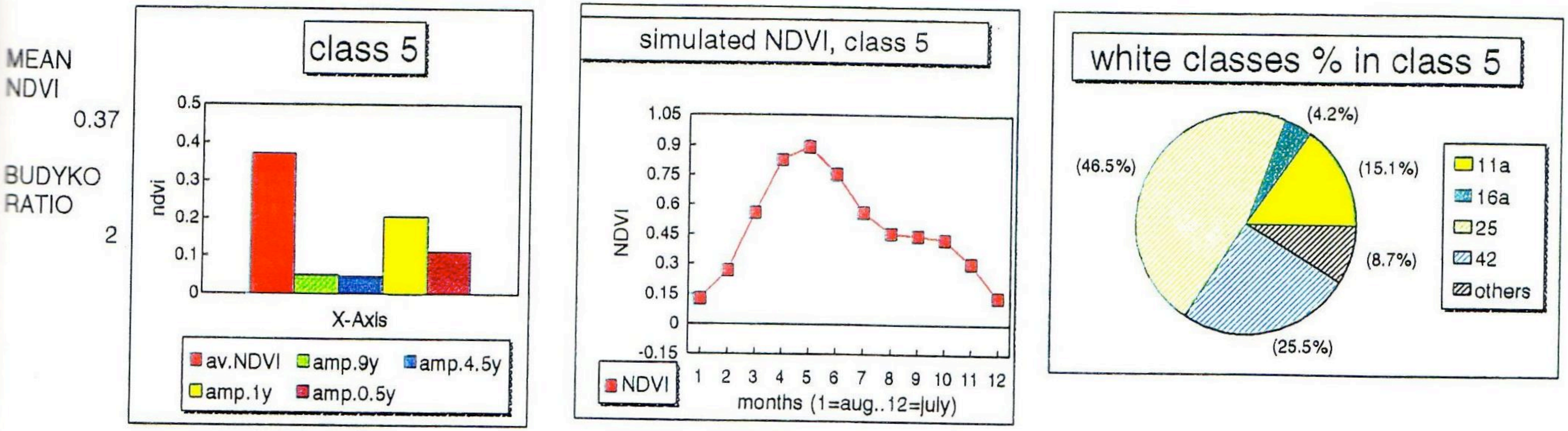
- 7.6 x 7.6 km

Isolines:

Budyko ratio Rn / P

Azzali and Menenti, 2000

Soil Vegetation Climate Complexes



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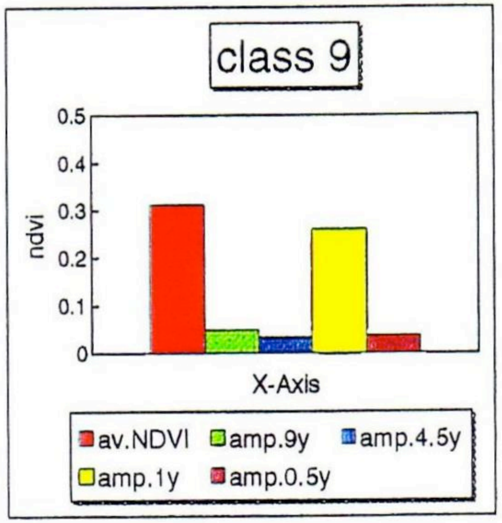
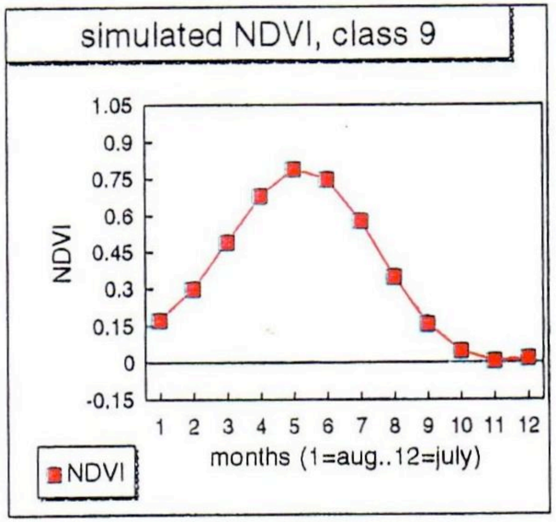
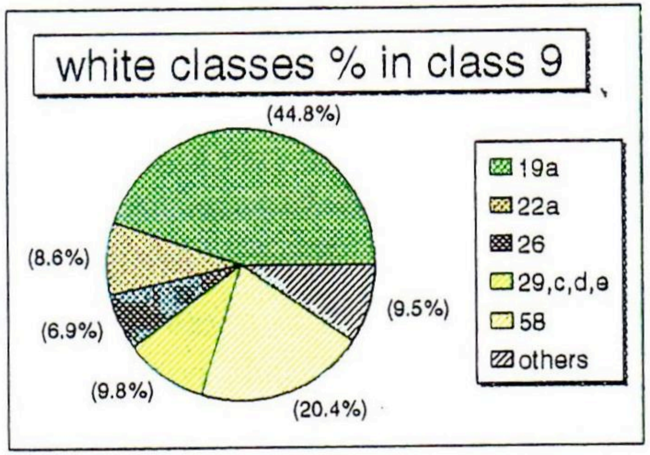
Soil Vegetation Climate Complexes

MEAN NDVI 0.31

BUDYKO RATIO 2.5







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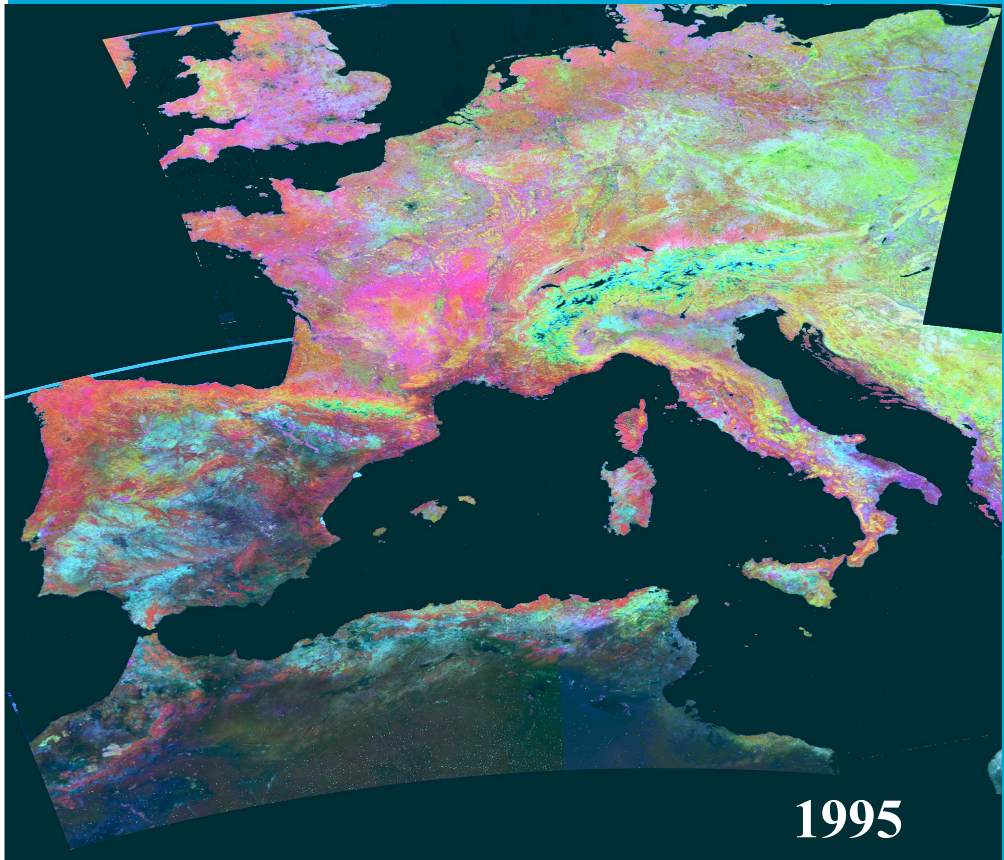
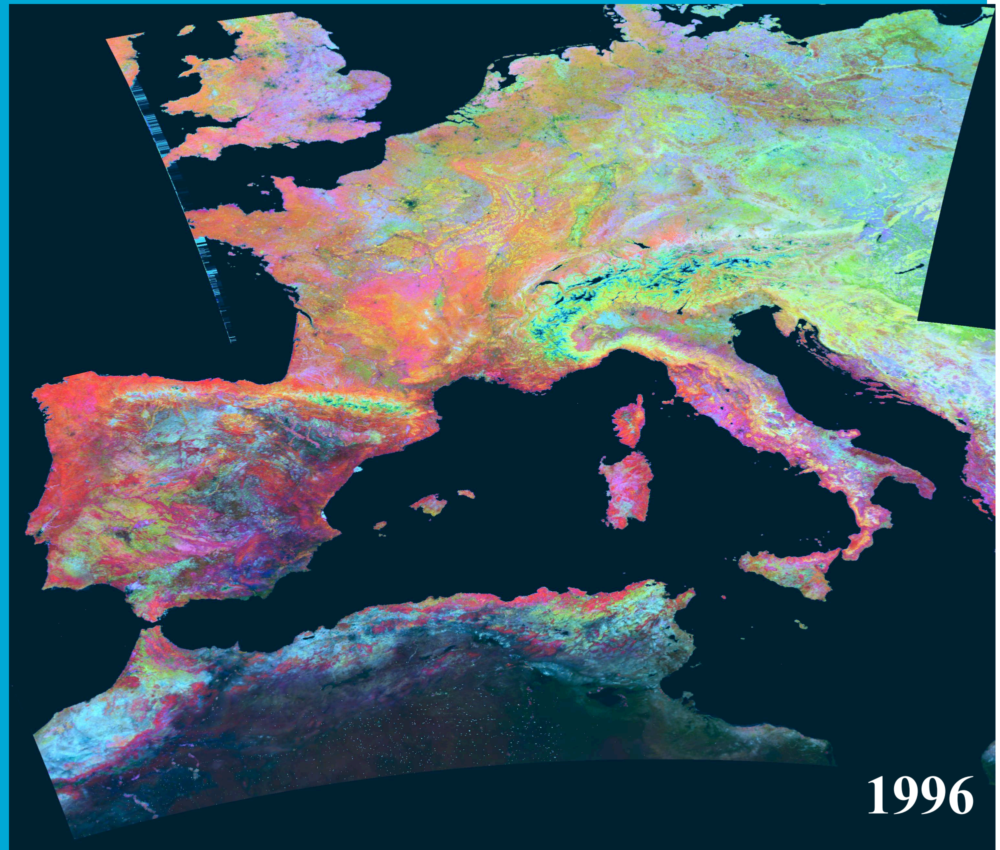
Interannual variability Europe – North Africa 1990 - 1997

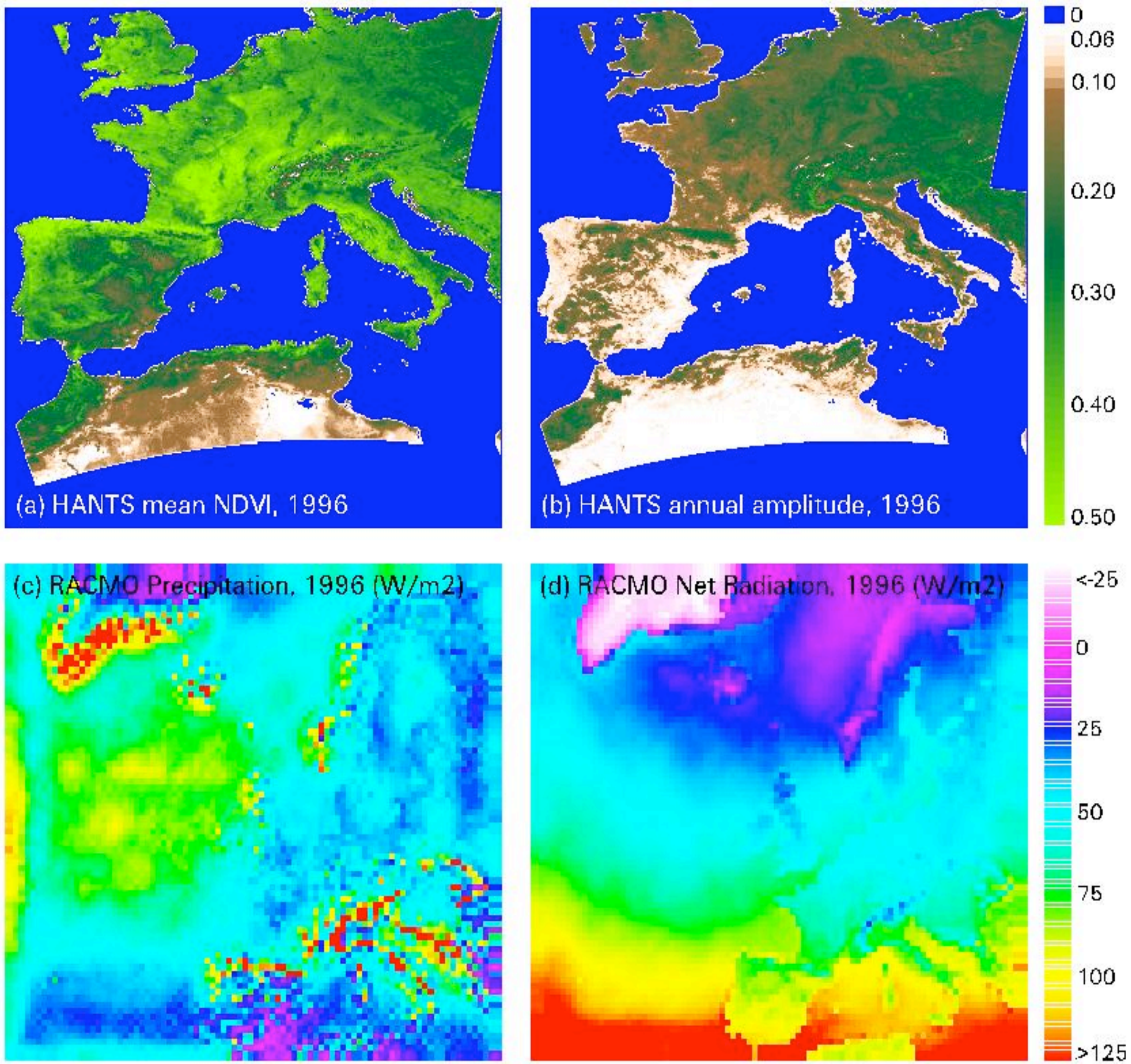




Map of HANTS (Harmonic Anallysis of Numerical Time Series) Fourier components of NDVI of 1995 (a) and 1996 (b); red = mean NDVI; green = amplitude of 1 year; blue = amplitude of 6 months

Vegetation phenology – aridity

AVHRR - mean **AVHRR - Ampl**



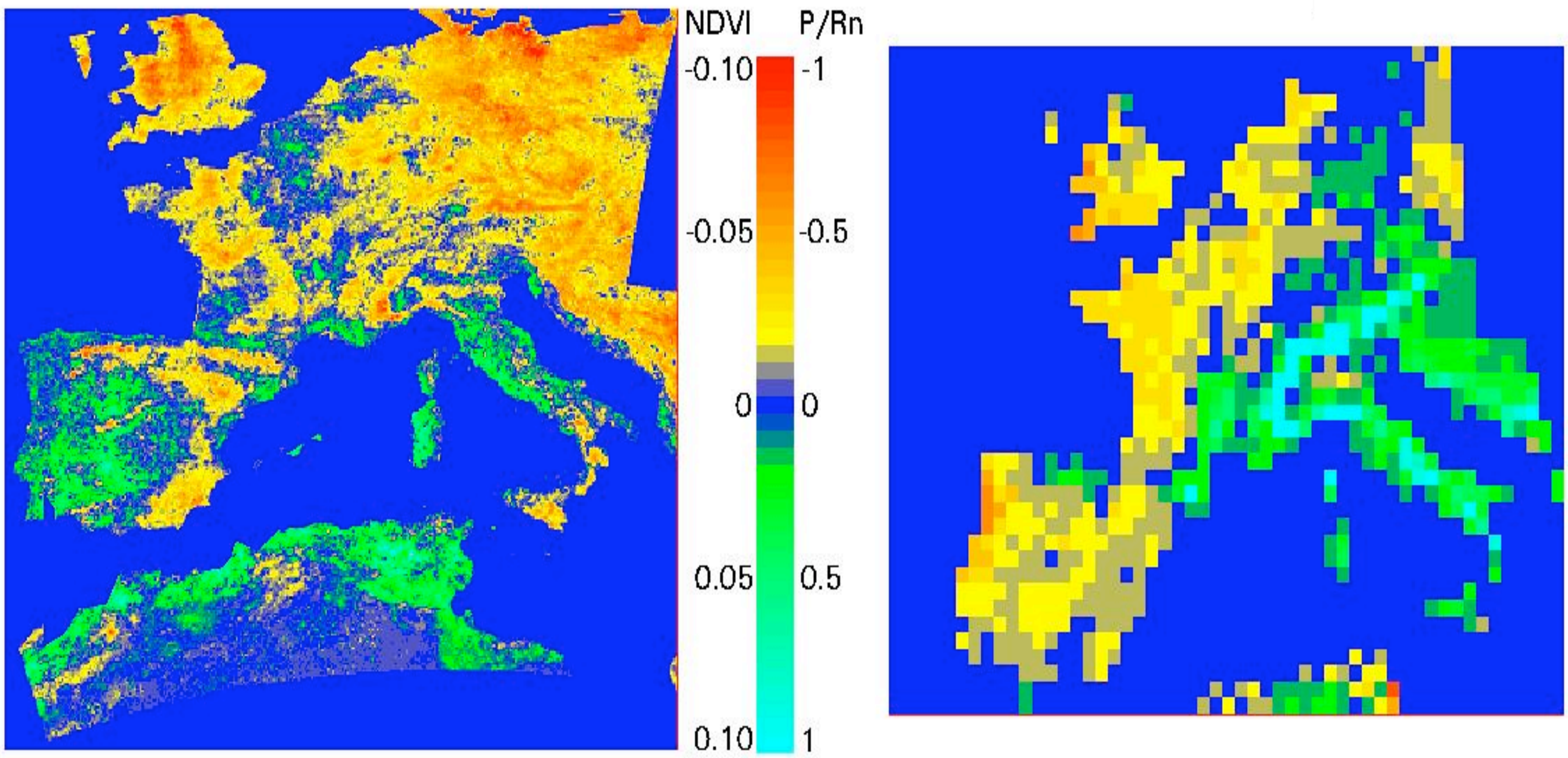
NWP - P **NWP - Rn**

- **Response of land surface**
- **change mean NDVI, yearly amplitude**
- **change P / Rn**
- **AVHRR aggregated at NWP resolution**
- **interannual variability**

Europe 1996 vs. 1997

•Mean NDVI 1996 - mean NDVI 1997

•P/Rn 1996 - P/Rn 1997



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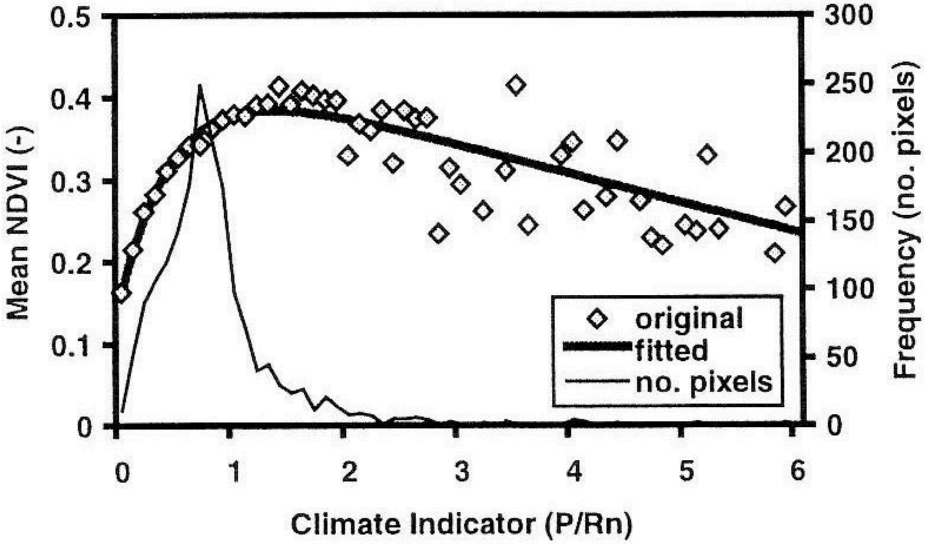
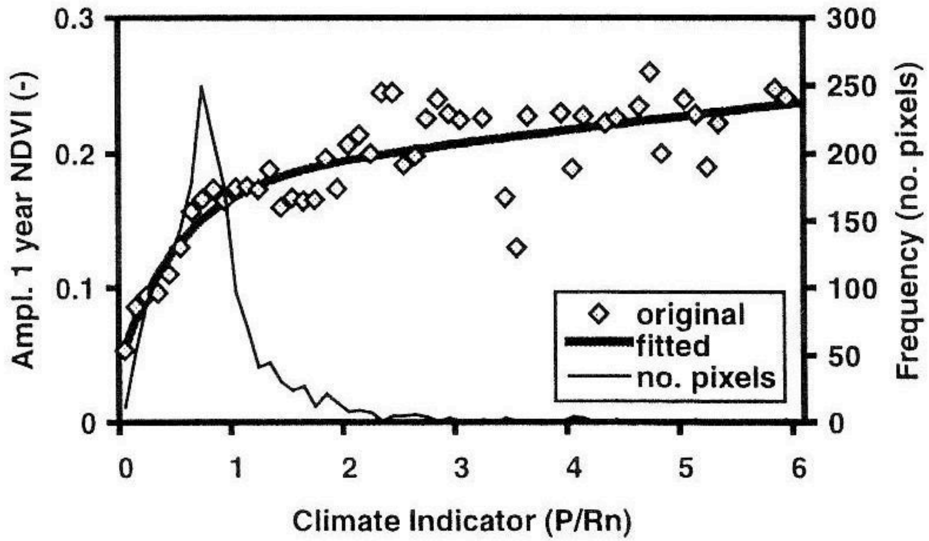
Spatial response of vegetation phenology

mean NDVi vs wetness **yearly amplitude NDVi vs wetness**

(a)



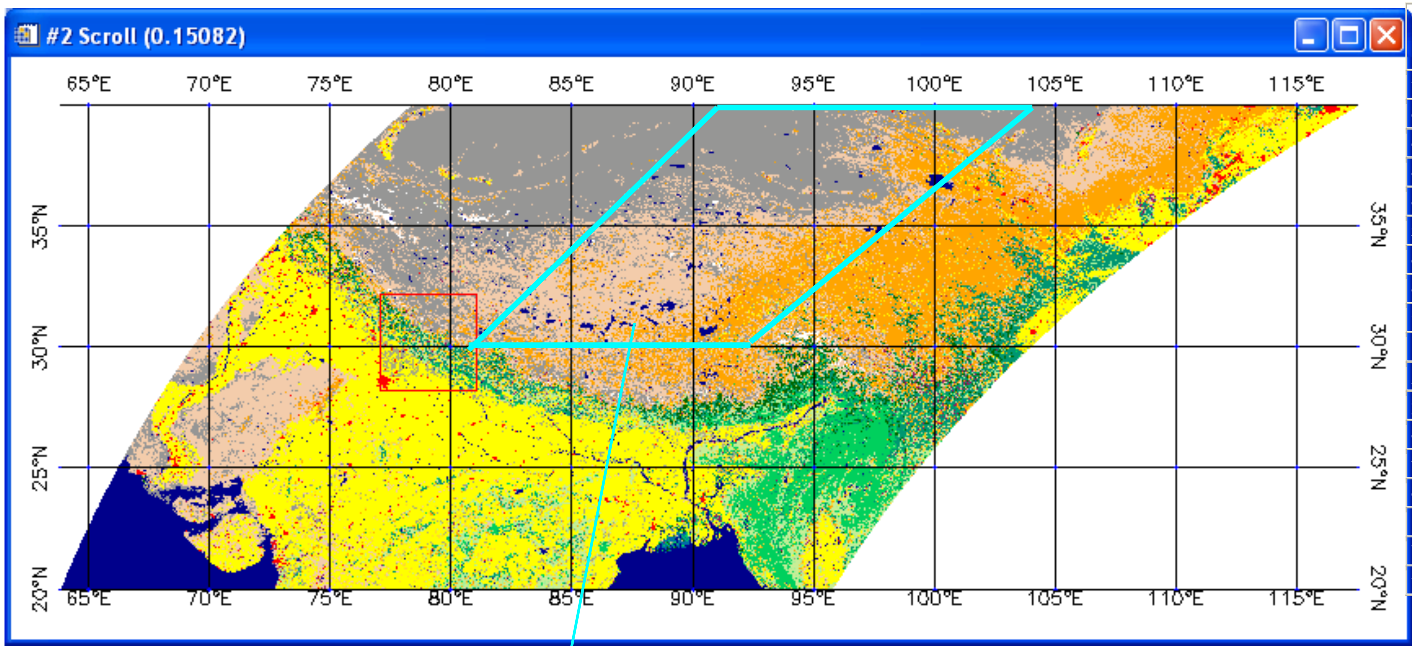
(b)



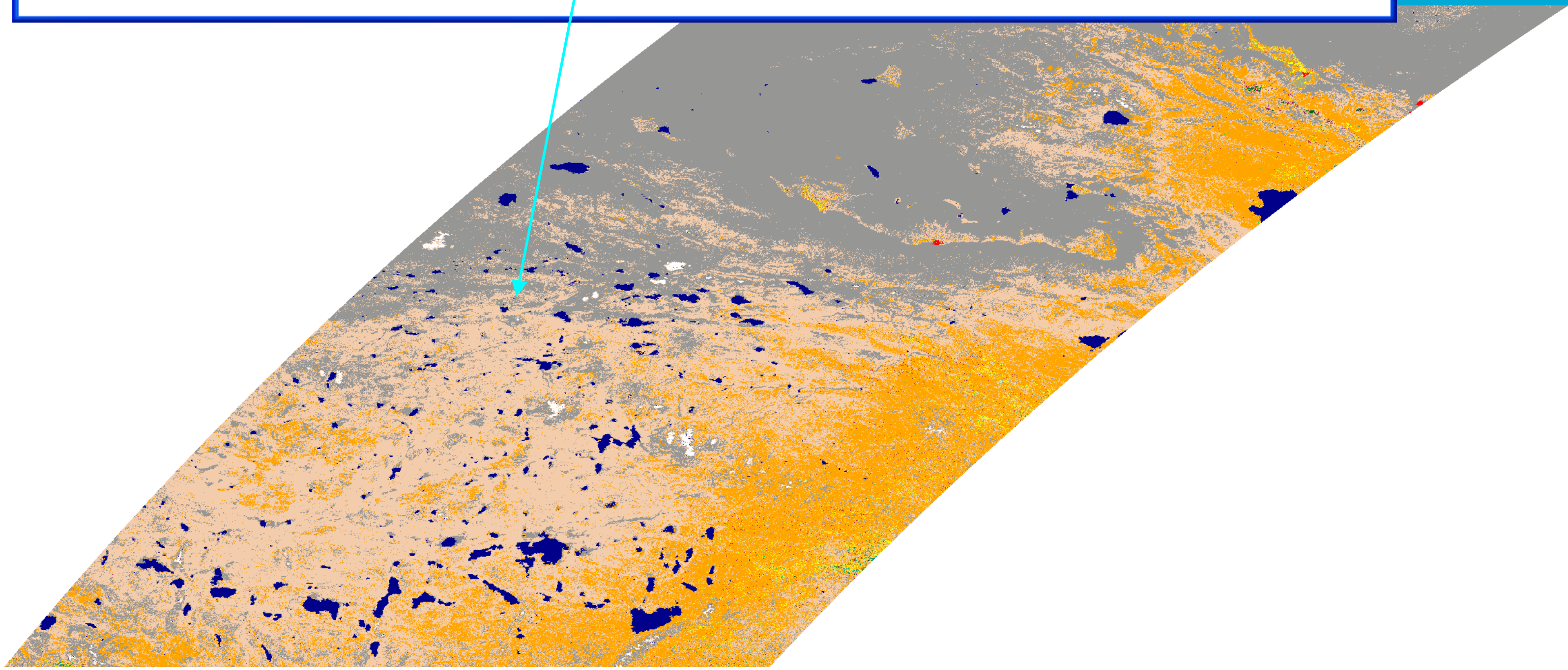
Case studies Tibet and Sichuan

2001 – 2005

Jia and Menenti, 2006

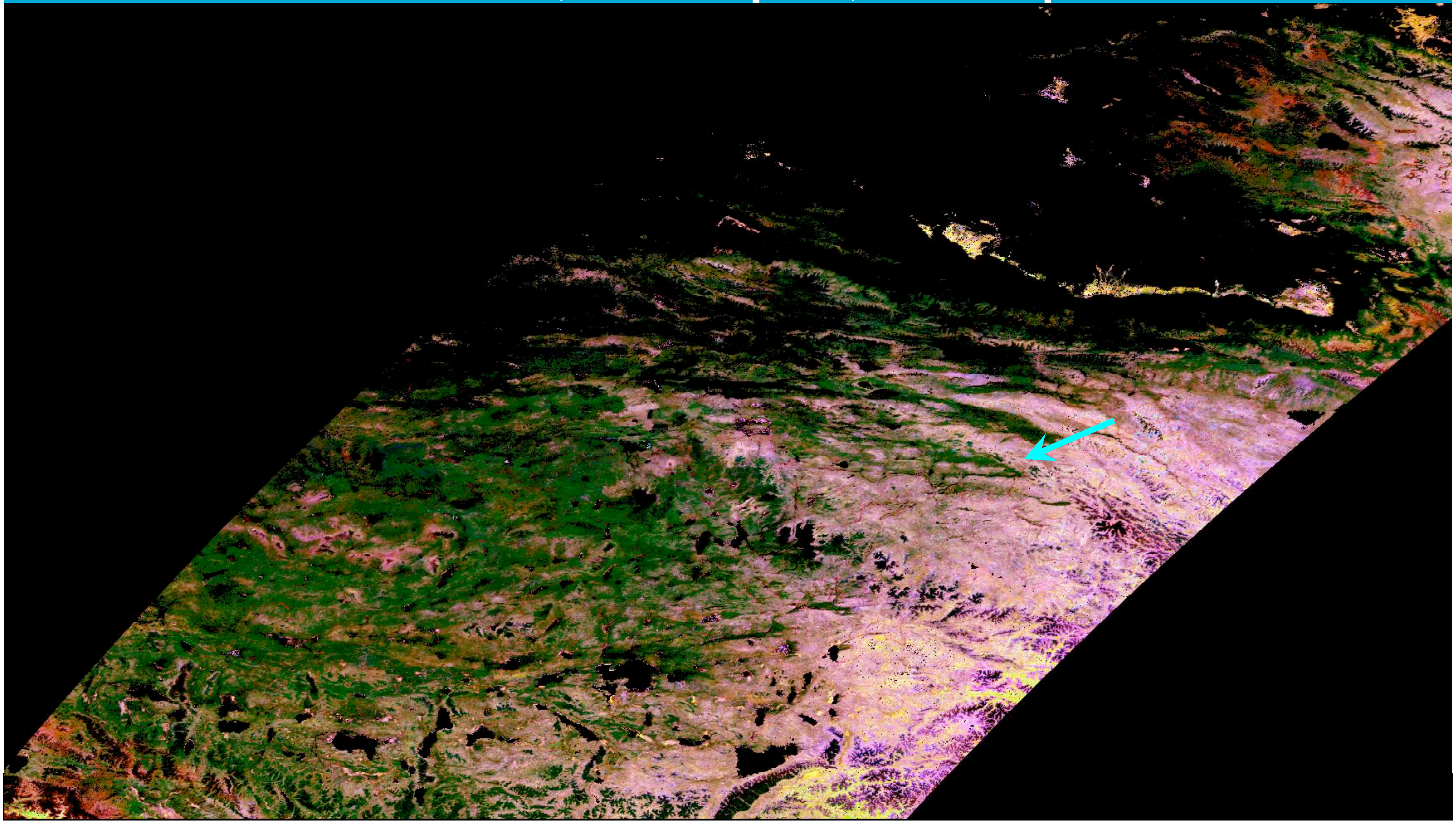


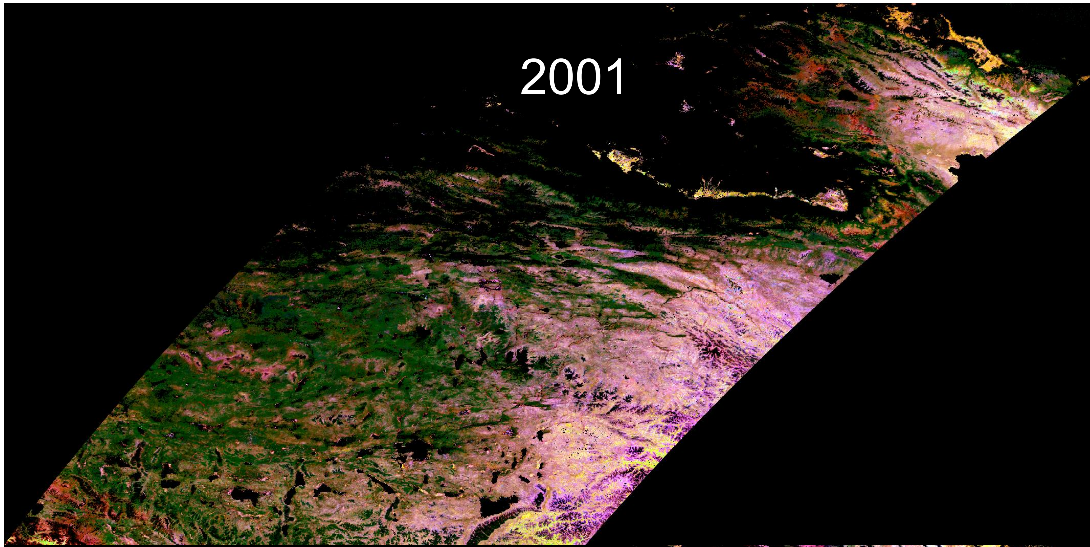
CLASSIFICATION	INDEX	COLOR
water	0	
evergreen needleleaf forests	1	
evergreen broadleaf forests	2	
deciduous needleleaf forests	3	
deciduous broadleaf forests	4	
mixed forests	5	
closed shrublands	6	
open shrublands	7	
woody savannas	8	
savannas	9	
grasslands	10	
permanent wetlands	11	
croplands	12	
urban and built-up	13	
cropland/natural vegetation	14	
snow and ice	15	
barren or sparsely vegetated	16	
unclassified	254	

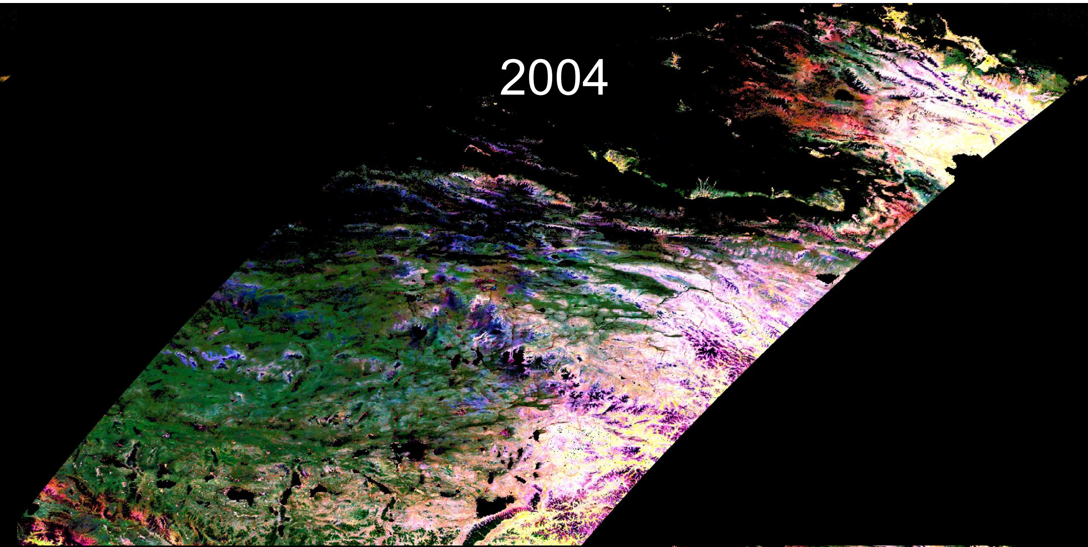


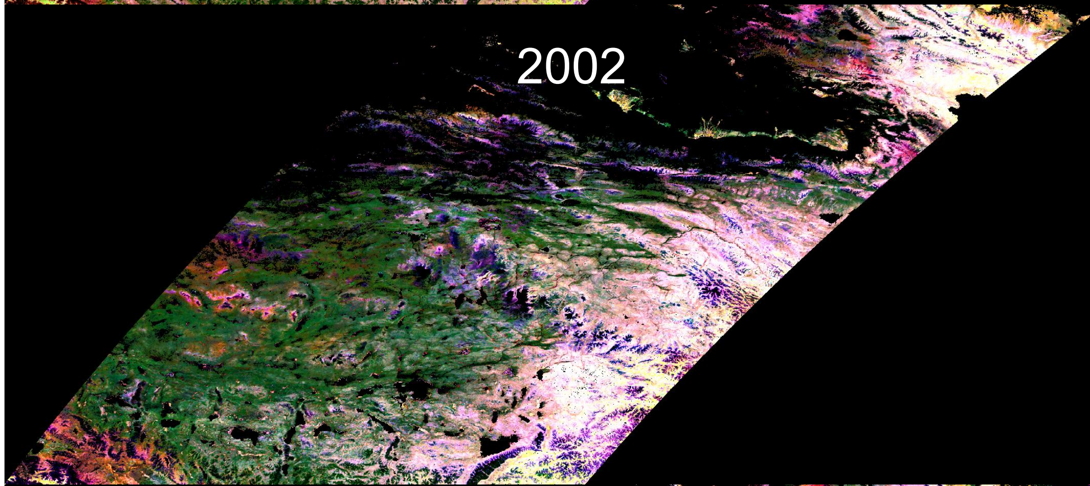
fAPAR 2001:

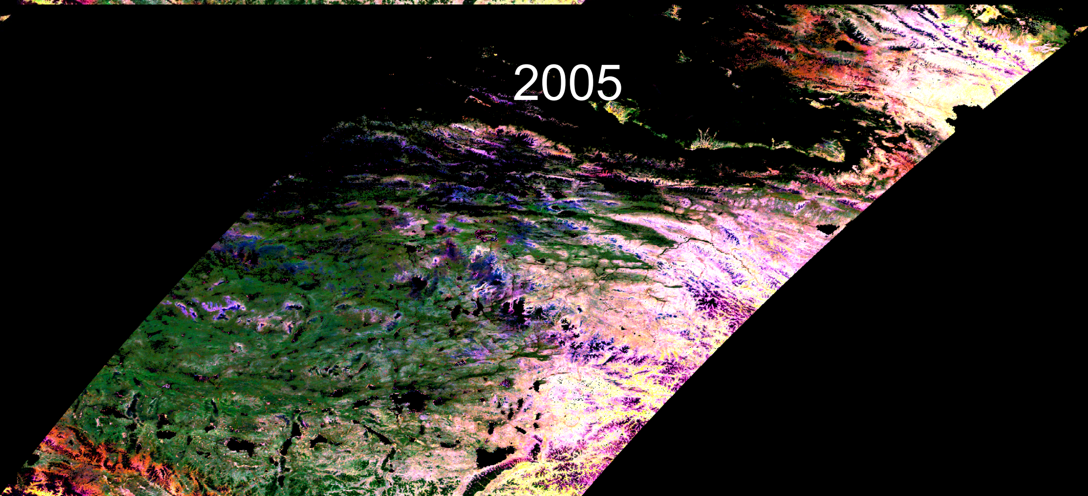
G = mean fAPAR, R = Amp-12, B = Amp-6

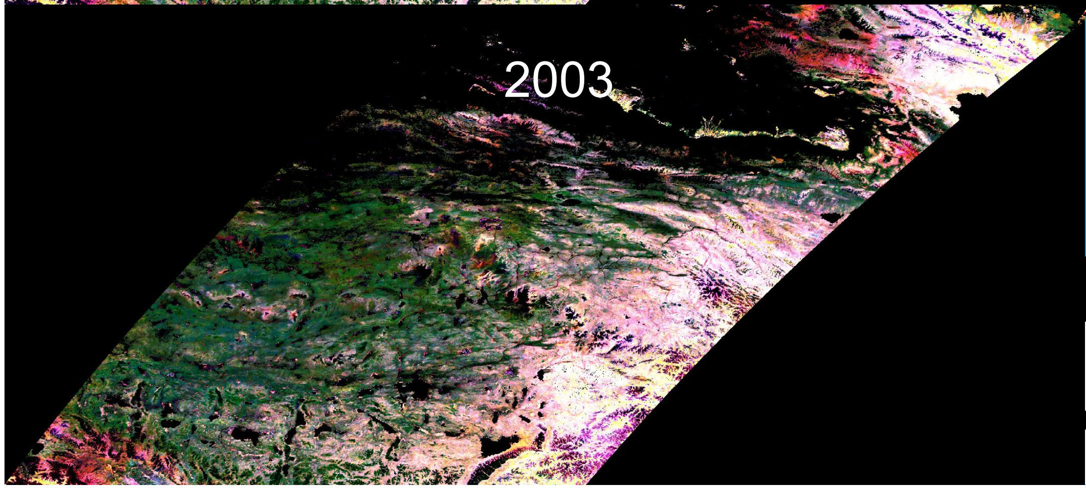










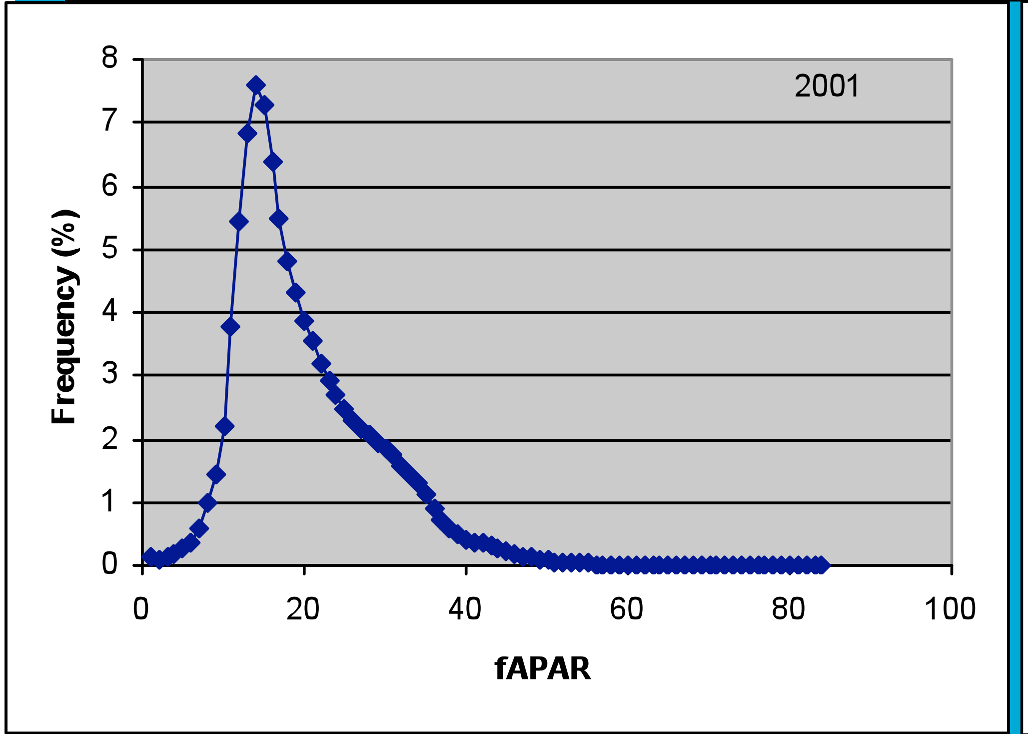


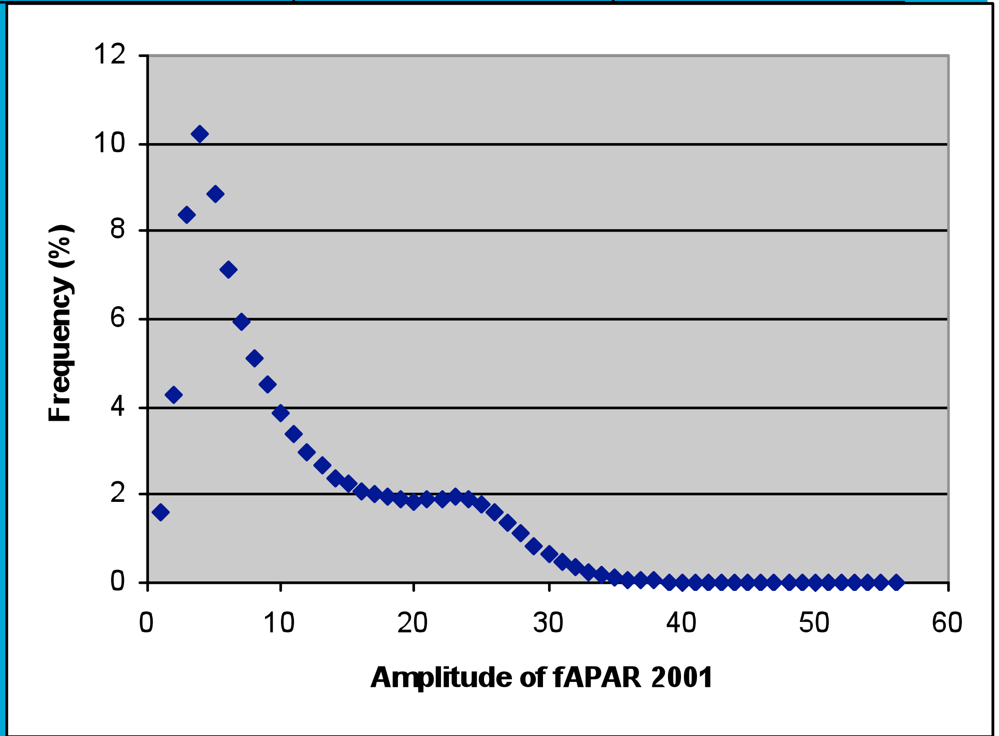
Phenology from RGB colour composite of Fourier coefficients

Same range of values for all years

Basic statistics on observations

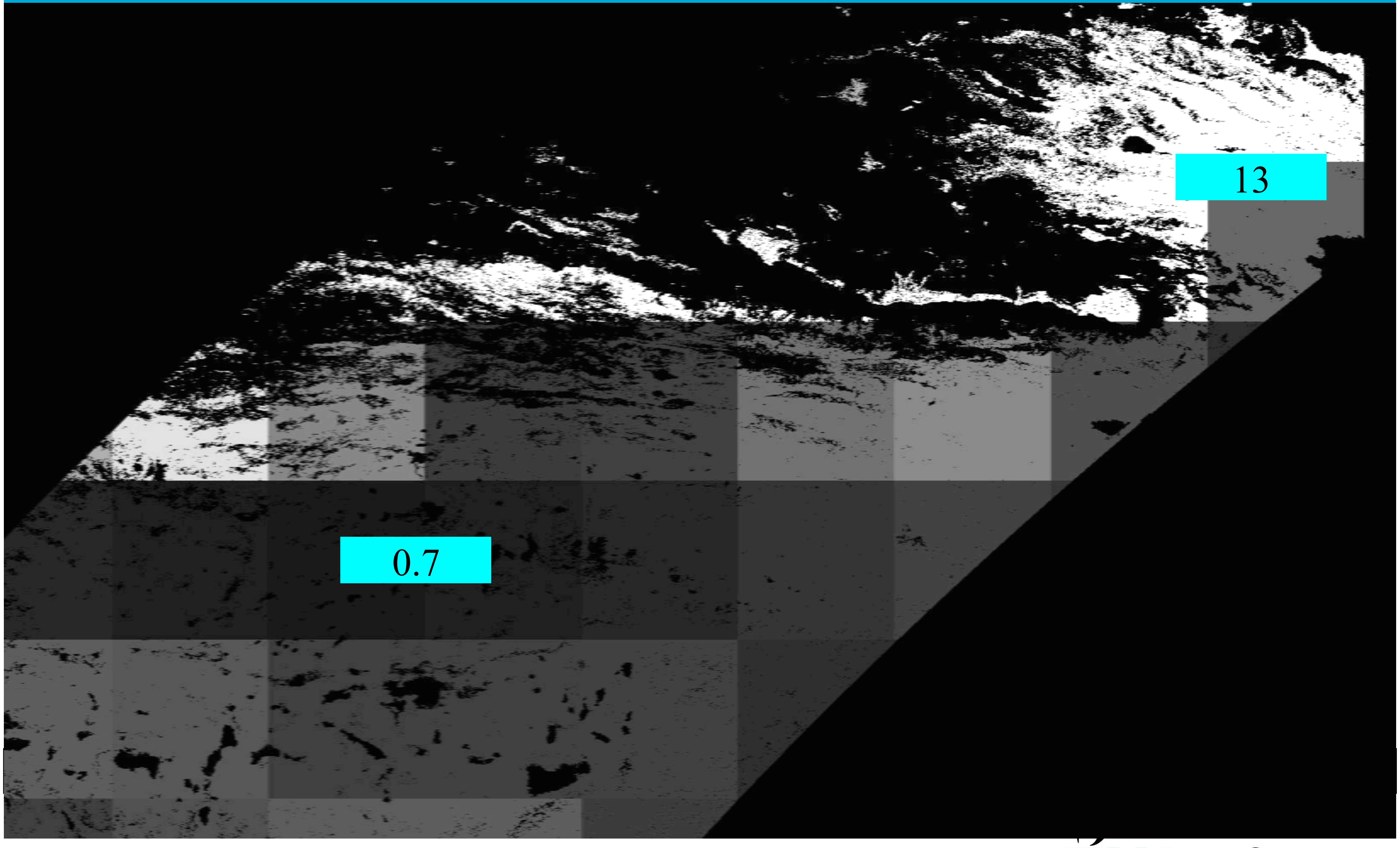
2001-2005	Δ fPAR	Δ A12	Δ A6	Δ Rn/P	
Mean	1.0661	-0.0612	0.4082	4.09	
Std	3.08	3.84	2.43	15.35	
Min	-42	-41	-43	-2.03	
Max	50	46	40	93.38	





Yearly Rn / P from NCEP data

2001 – 2005 200 km x 200 km grid



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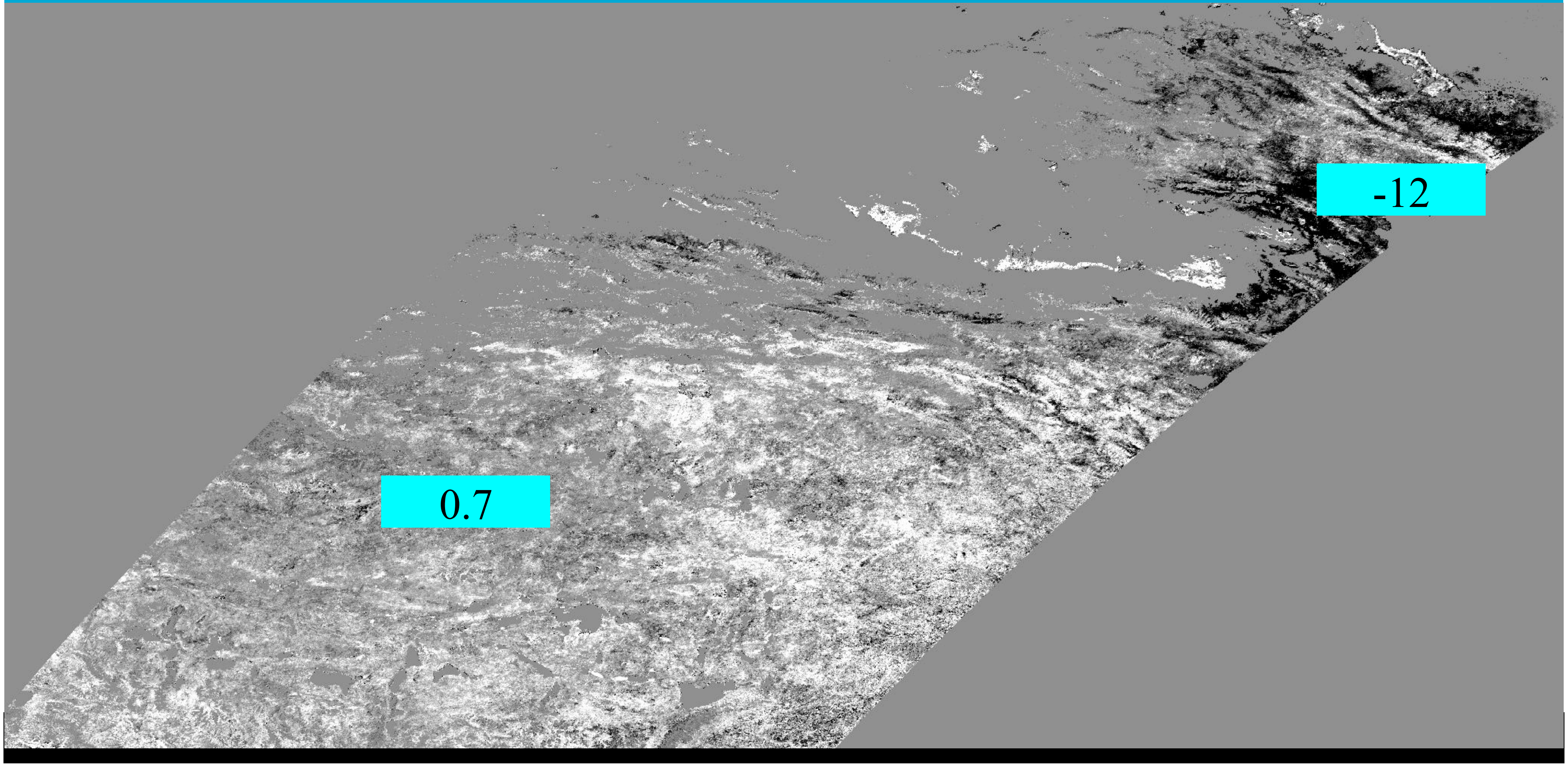
fAPAR 2001 – fAPAR 2005

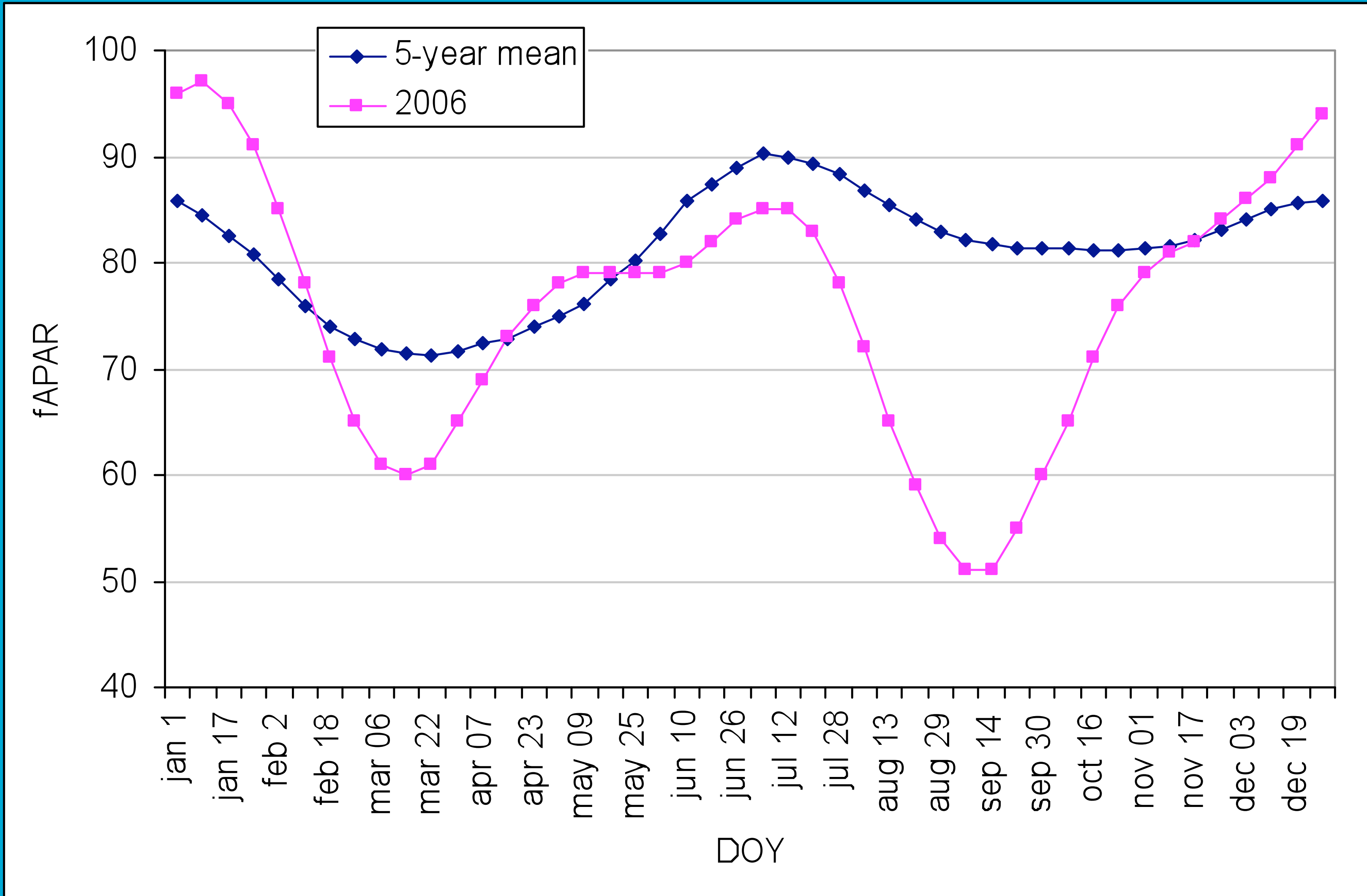


Vegetation response to weather phenological anomalies and drought

Jia and Menenti, 2009

- Cloud-free time series of land surface variables observed by optical remote sensing
- Detection of water deficit by combining anomalies in vegetation greenness and thermal properties

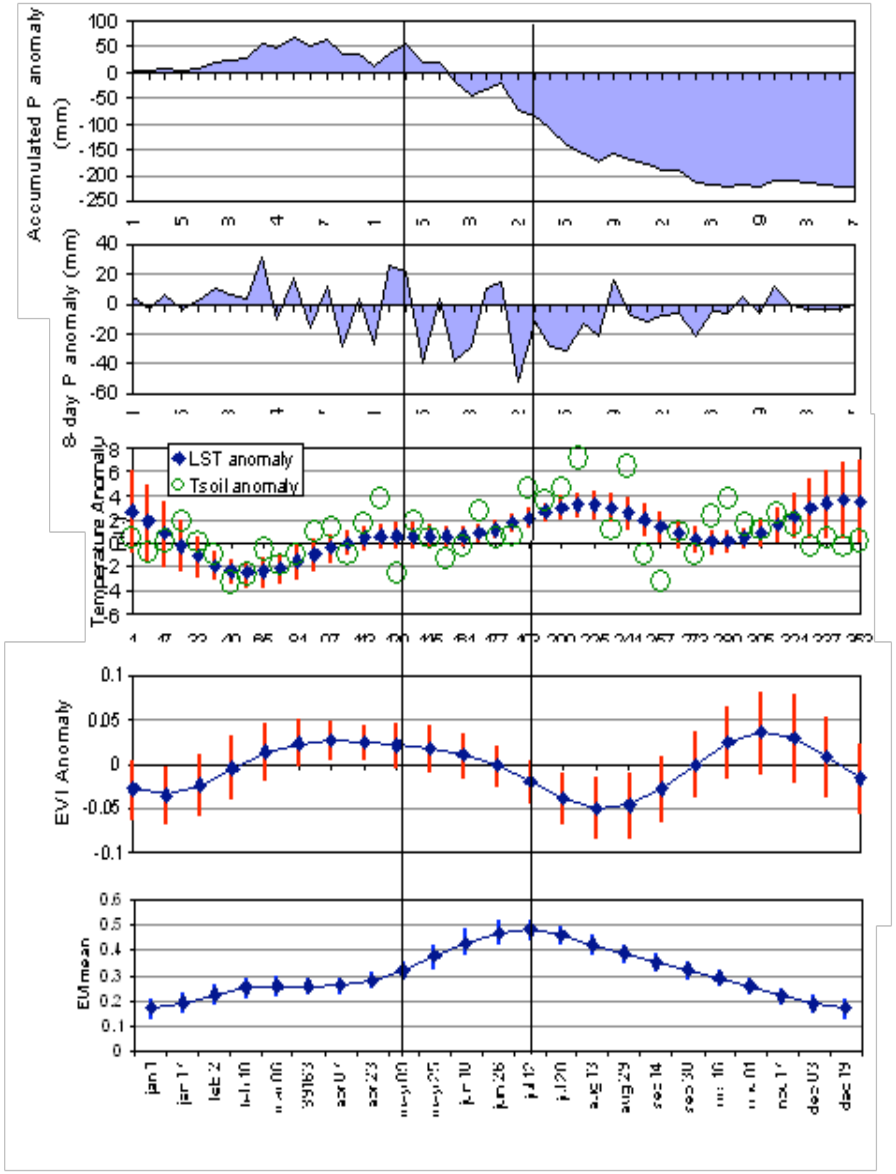
Anomaly:
Deviation of current situation from historical average



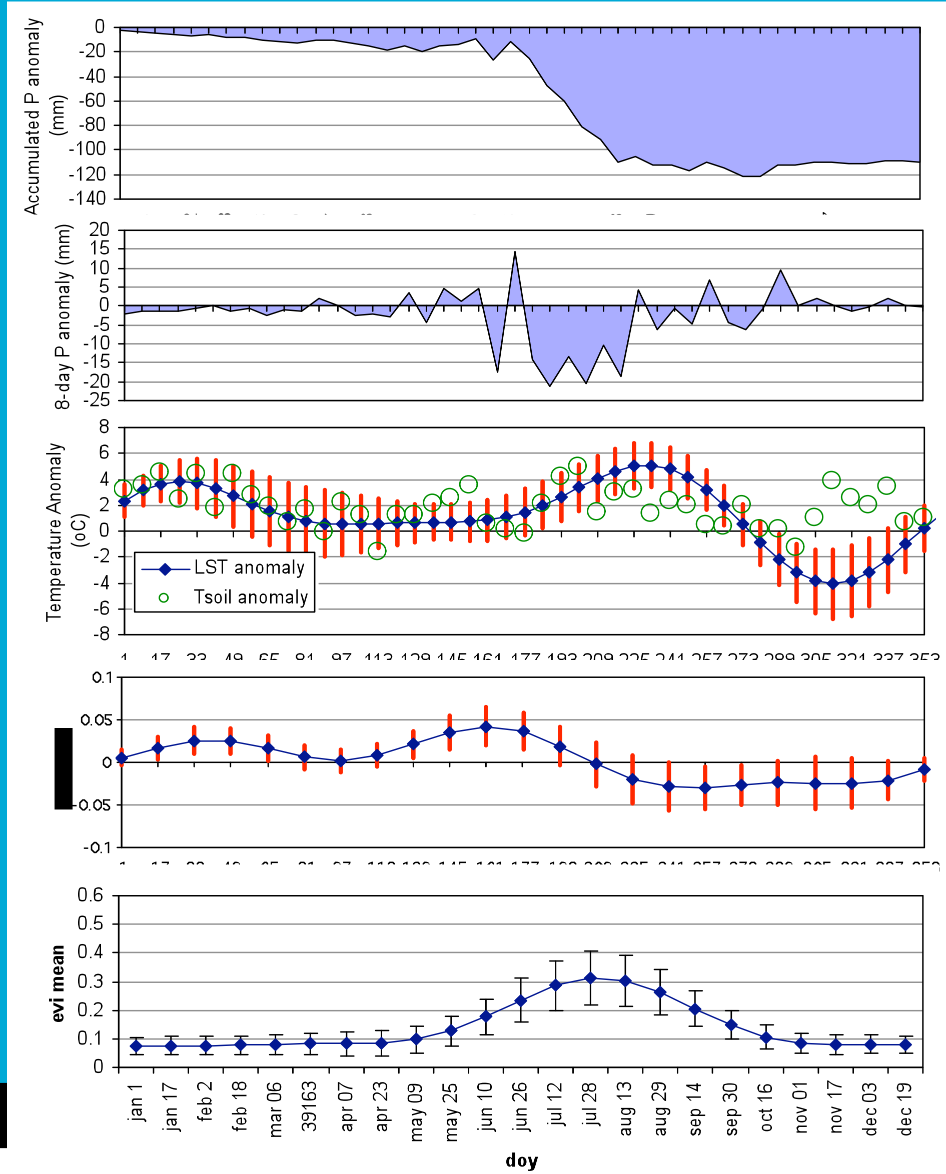
Sichuan-Chongqing drought, 2006

Drought monitoring by detecting anomalies

Crop land in Sichuan



Natural grassland in Tibet Plateau



Drought early warning by detecting anomalies

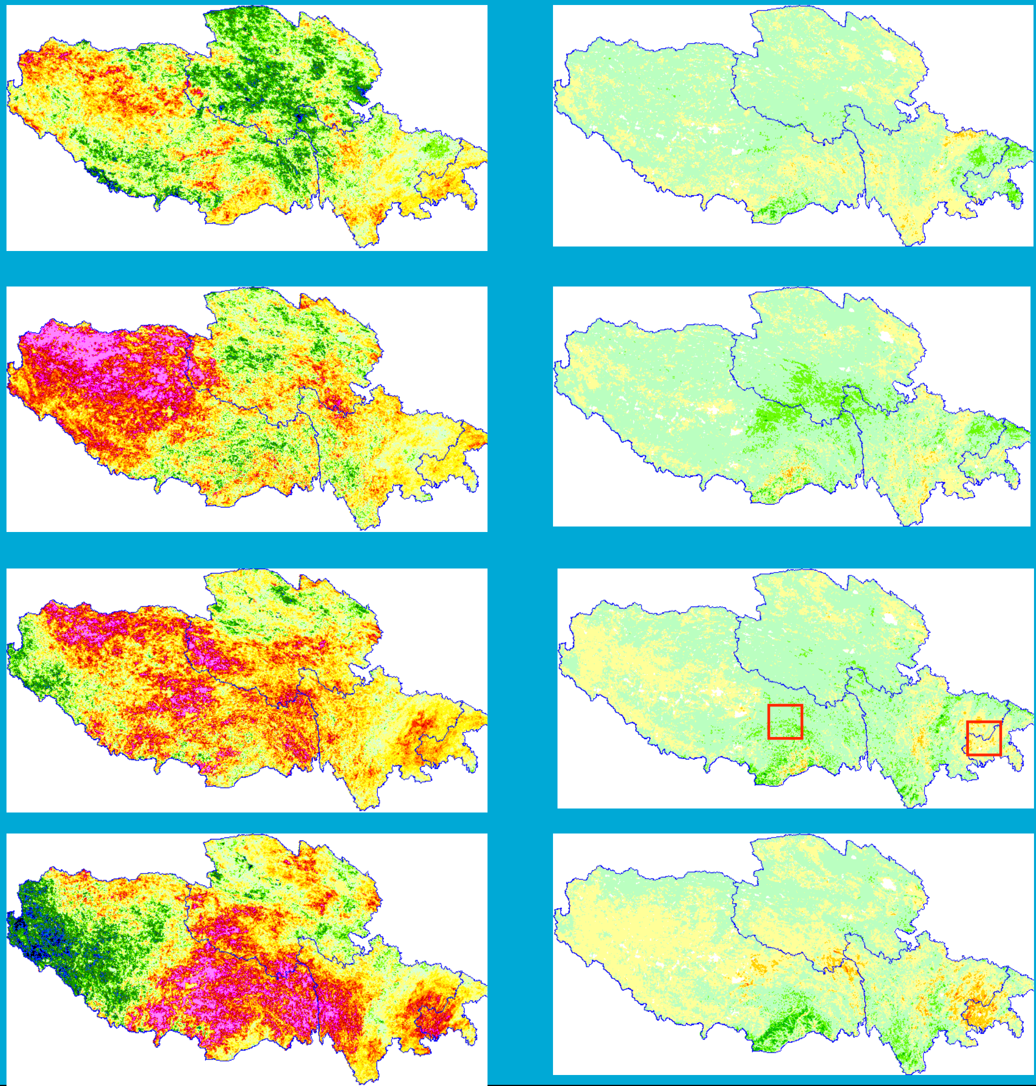
LST anomaly | EVI anomaly

9 May

10 June

12 July

13 Aug



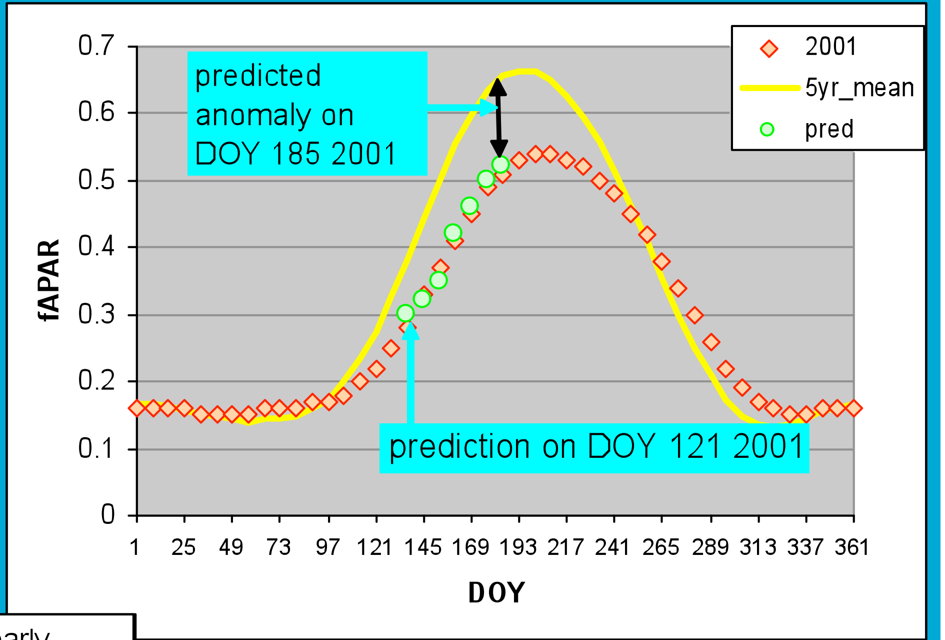
Tibet Plateau and Sichuan-Chongqing,

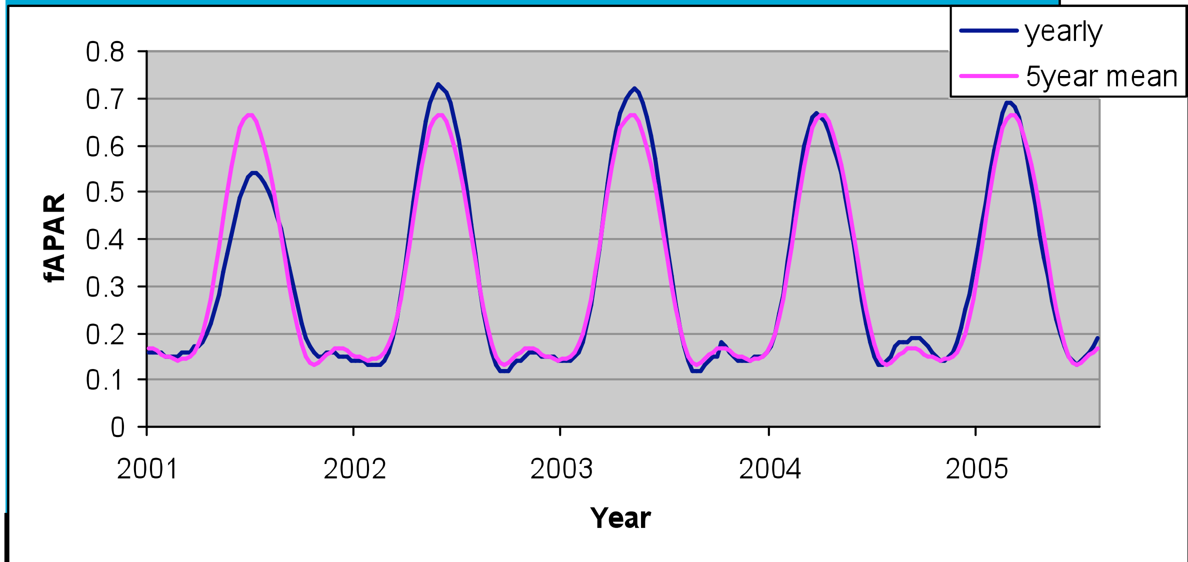
2006

TU Delft

Early warning and prediction of drought events

Prediction: through modeling of time series by Fourier series, wavelets, Markov chains, etc. per pixel over entire country.



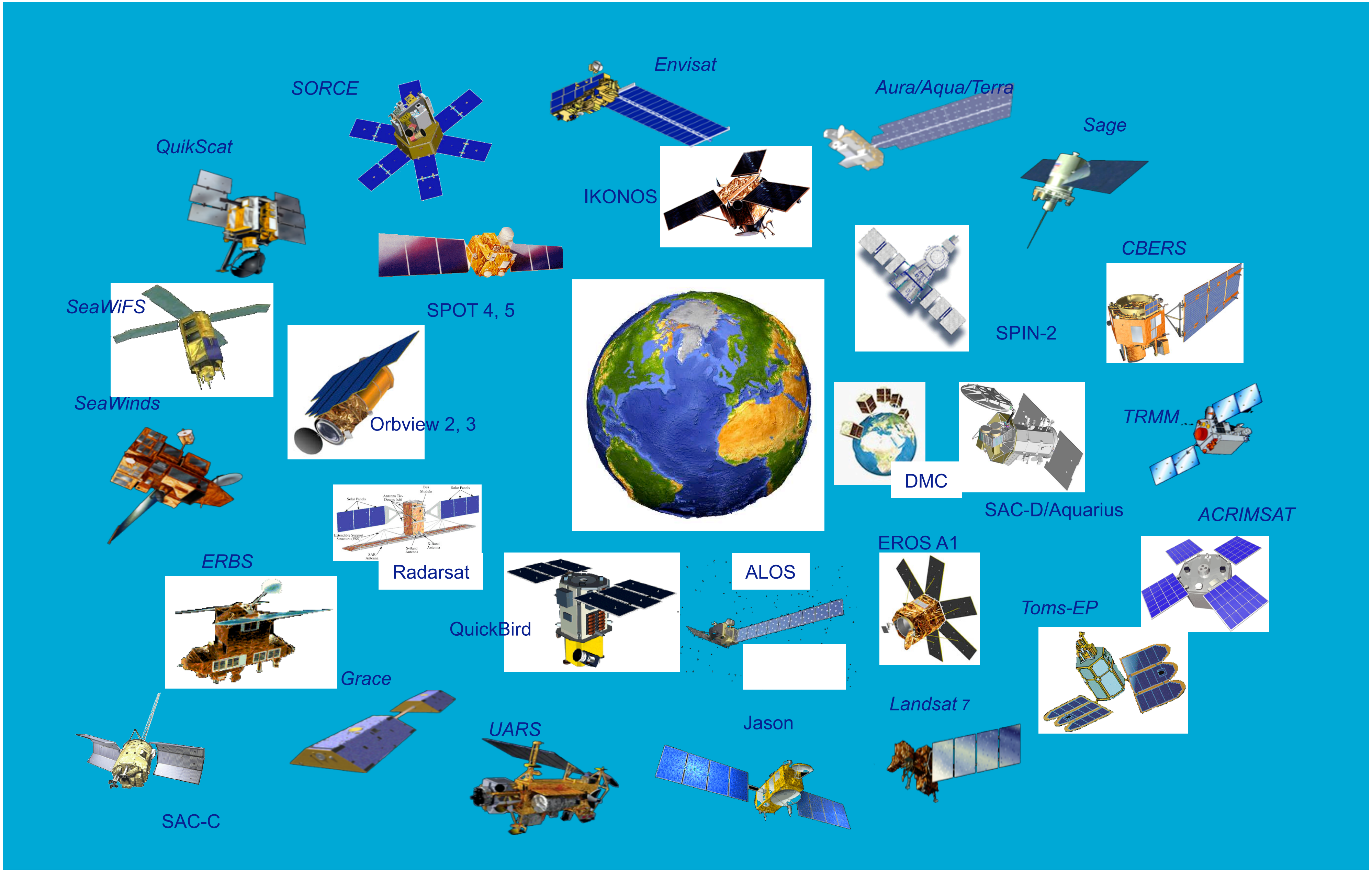


TUDelft

Near and far future:

richness of observation system

240 satellites under development for Earth Observation



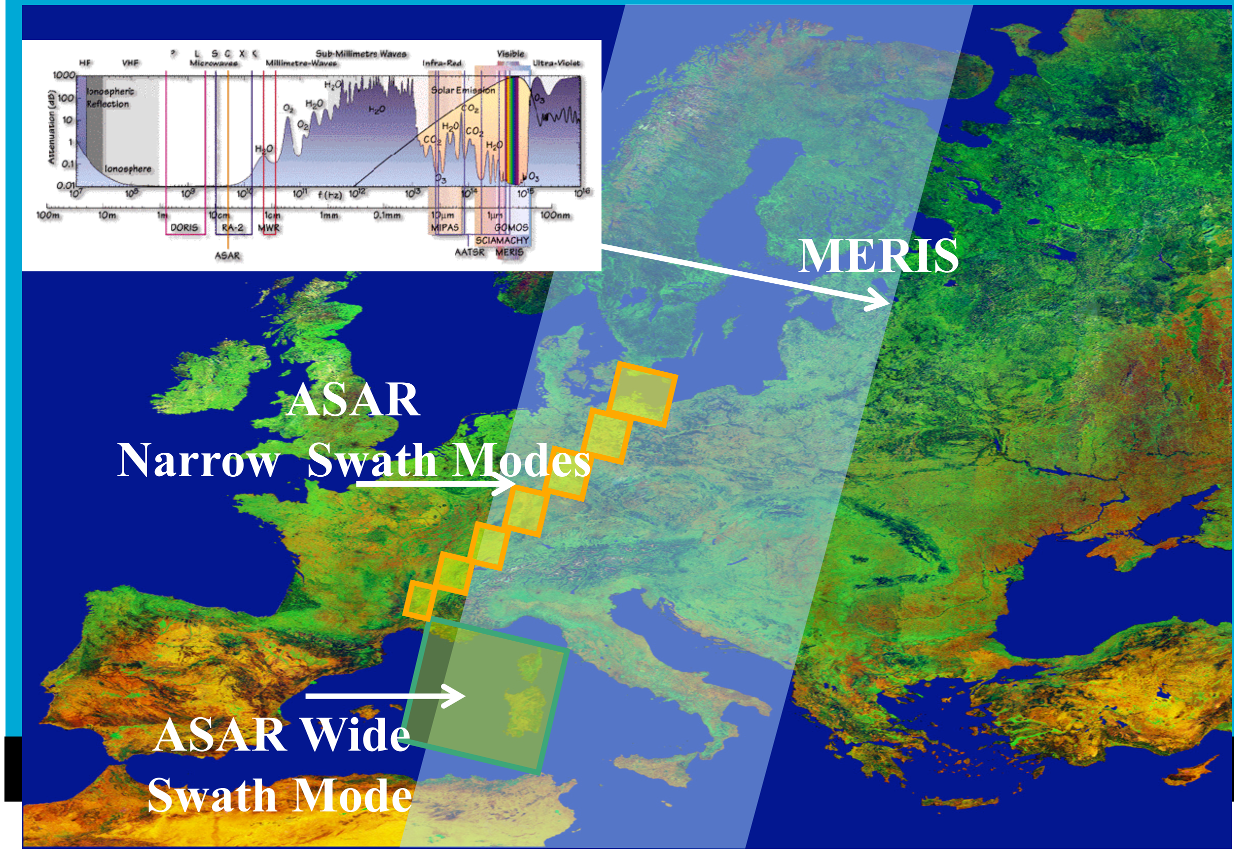
SORCE
Envisat
Aura/Aqua/Terra
Sage
QuikScat
IKONOS
CBERS
SPOT 4, 5
SeaWiFS
SPIN-2
SeaWinds
Orbview 2, 3
TRMM
DMC
SAC-D/Aquarius
ACRIMSAT
EROS A1
ERBS
Radarsat
ALOS
Toms-EP
QuickBird
Grace
Landsat 7
UARS
Jason
SAC-C

ENVISAT Land Observations

- How ?
- Signals
- operational systems
- precisely defined?
- Large areas or local?

- What?

- Collect, process and analyze global observations
- procedure to measure and interpret trends



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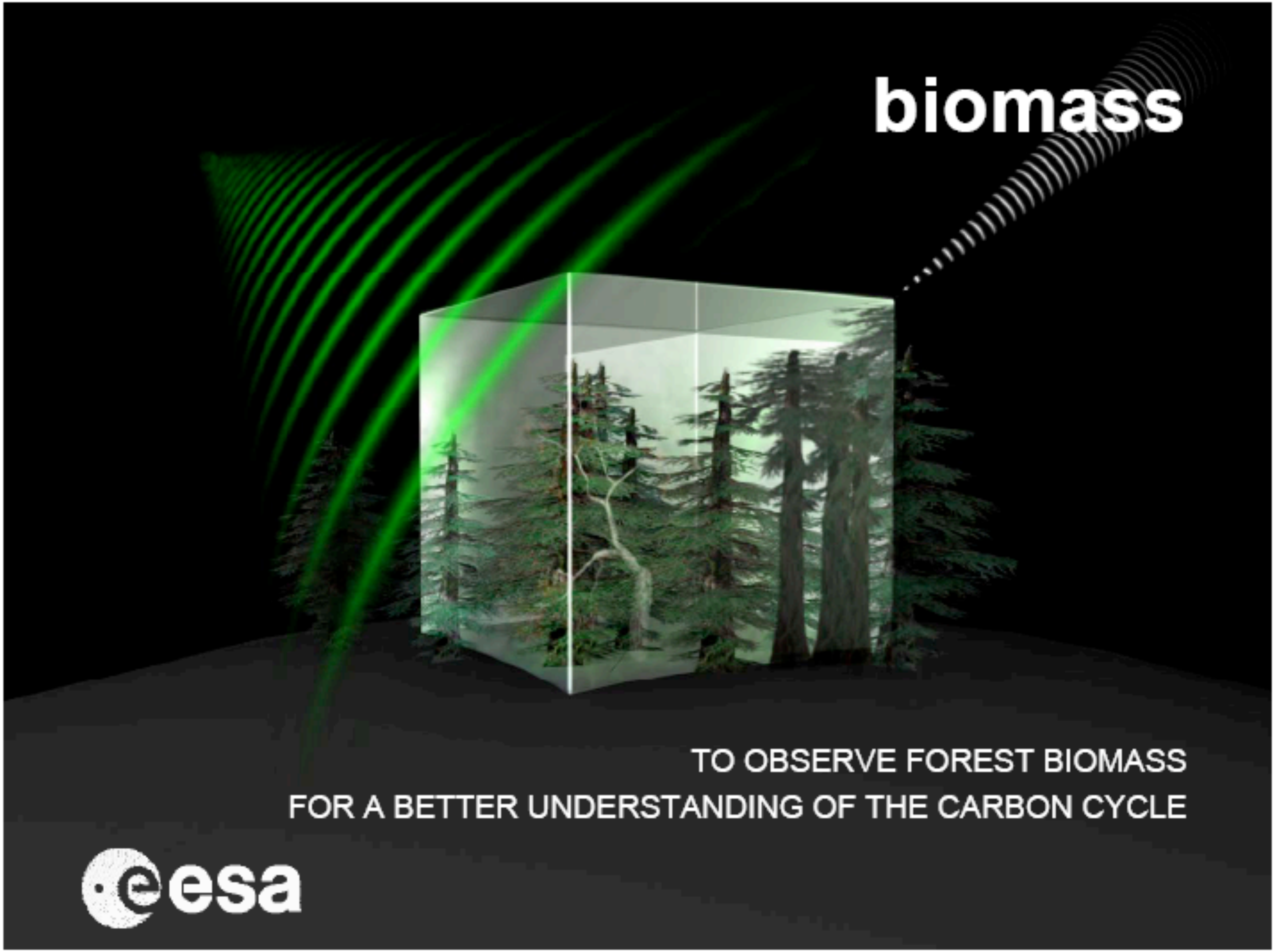
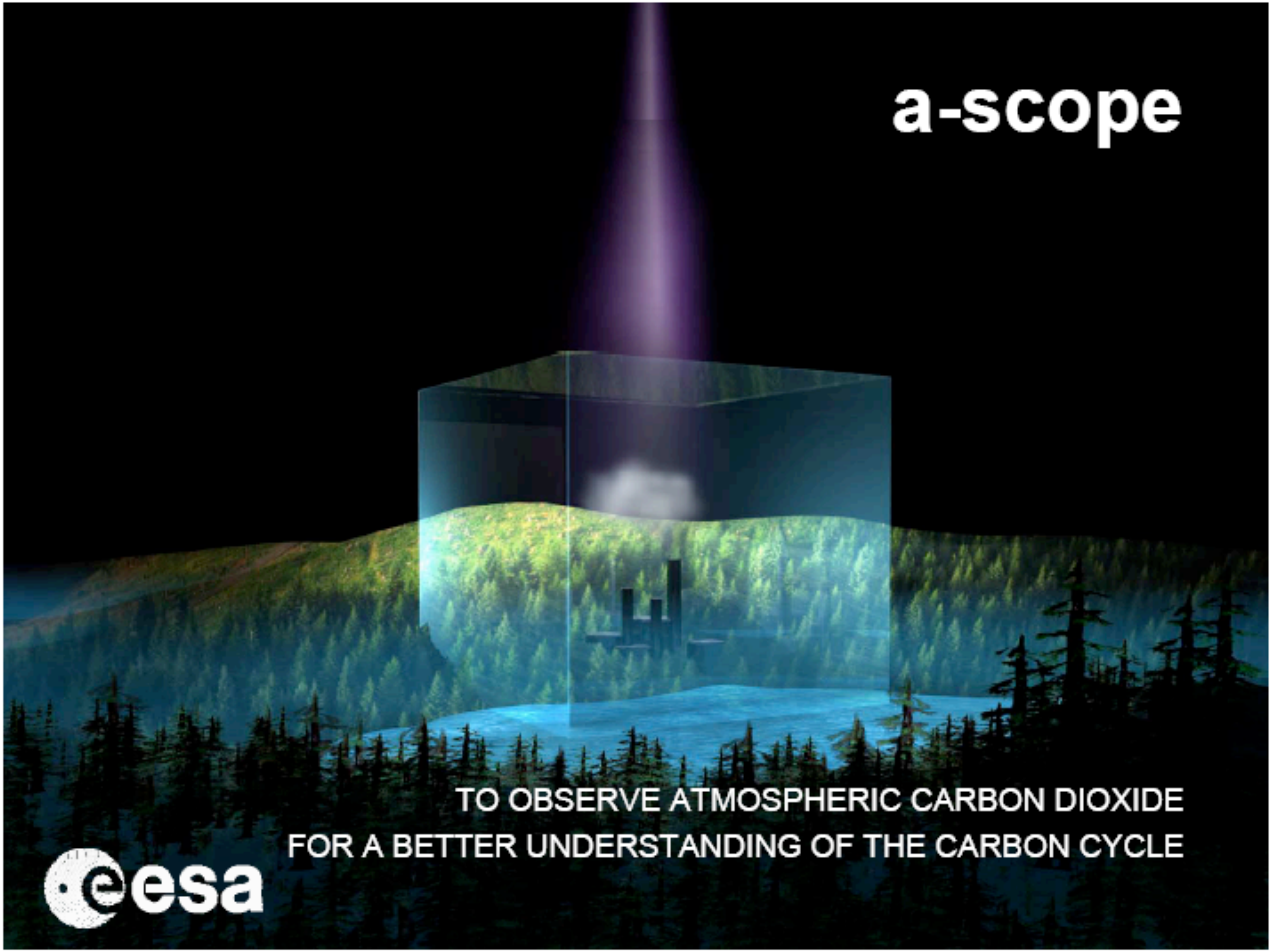
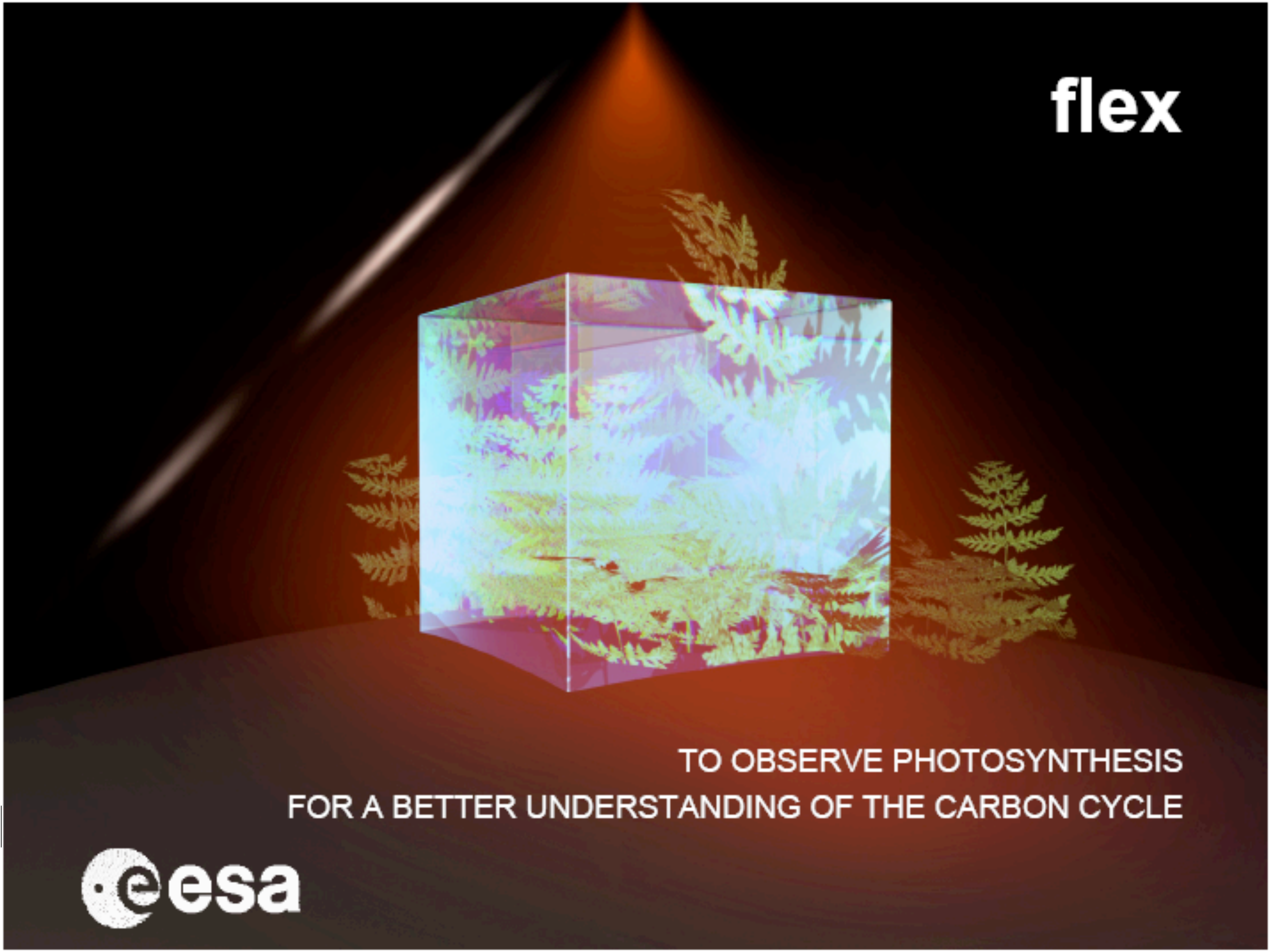
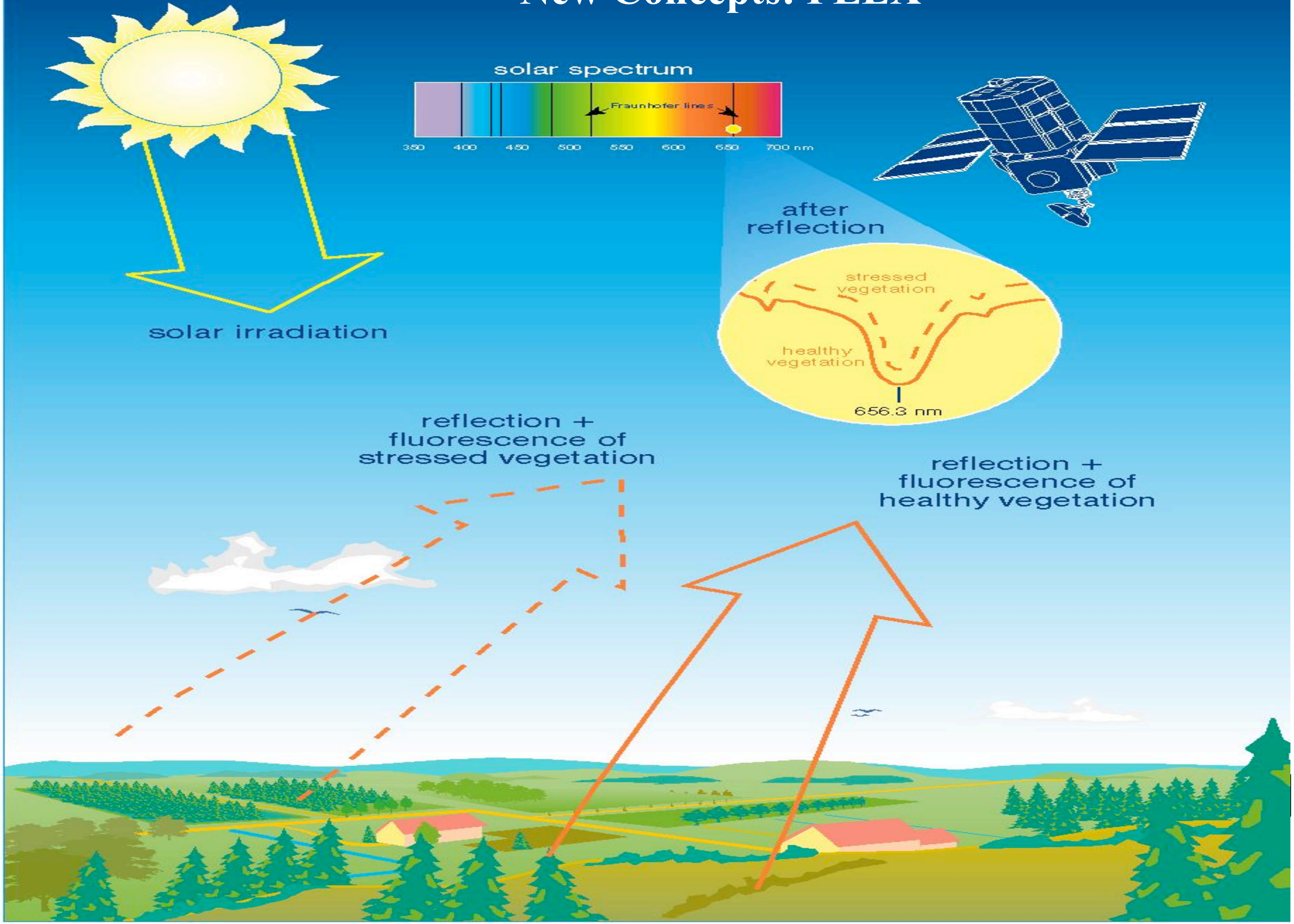

biomass
TO OBSERVE FOREST BIOMASS
FOR A BETTER UNDERSTANDING OF THE CARBON CYCLE
esa

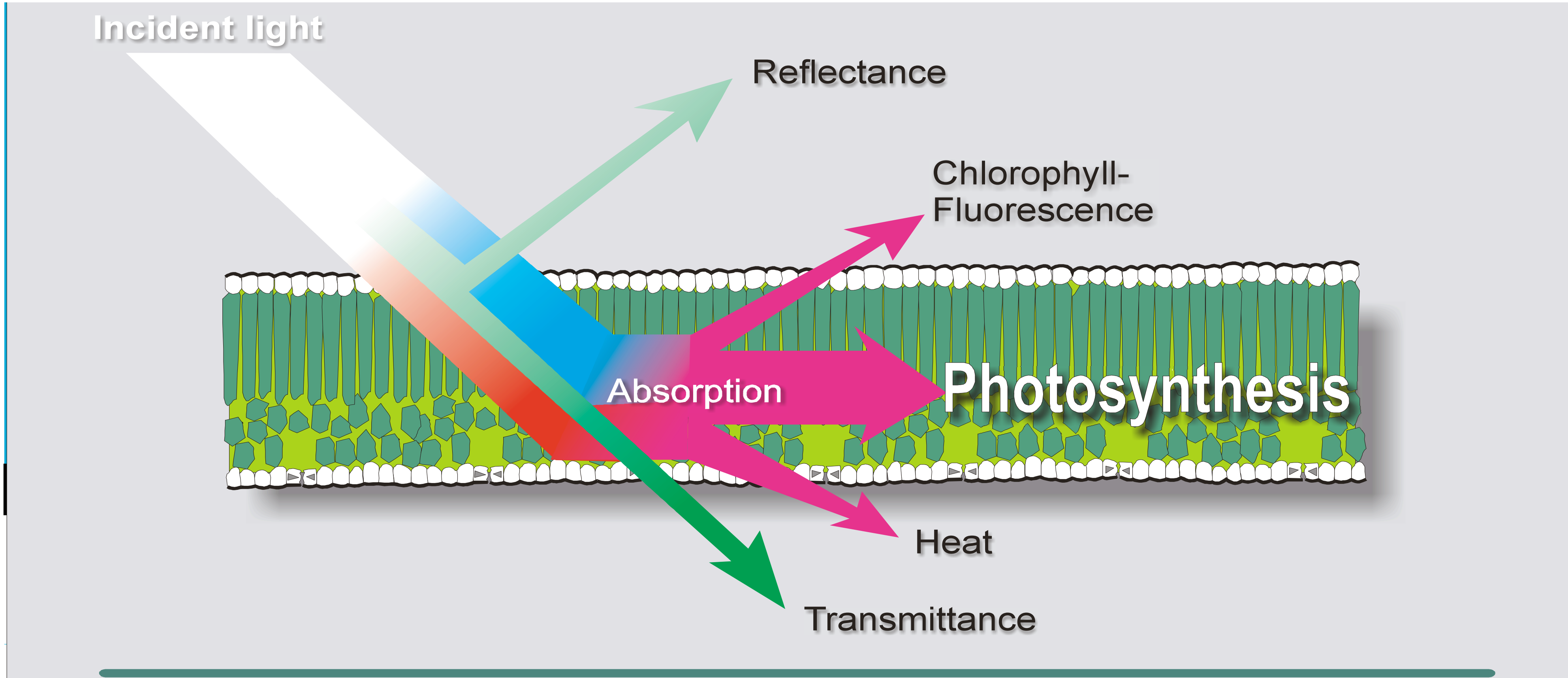

a-scope
TO OBSERVE ATMOSPHERIC CARBON DIOXIDE
FOR A BETTER UNDERSTANDING OF THE CARBON CYCLE
esa


flex
TO OBSERVE PHOTOSYNTHESIS
FOR A BETTER UNDERSTANDING OF THE CARBON CYCLE
esa

New Concepts: FLEX



FLEX Goals


Incident light
Reflectance
Chlorophyll-
Fluorescence
Absorption
Photosynthesis
Heat
Transmittance

University of Karlsruhe

FLEX
Changes of Fluorescence ratios

(Buschmann and Lichtenthaler: Journal of Plant Pyhsiology 152: 297-314 (1998))

BOTANIK II

	variegated / green	photoinhibition	water deficiency	sun exposure	mite attack	heat treatment	UV-A treatment	diuron inhibition	Aurea / green leaf	N-deficiency	lower / upper leaf side
F440/F690	↗	↗	↗	↗	↗	↘	↘	↘	→	↗	↗
F440/F740	↗	↗	↗	↗	↗	↘	↘	↘	↗	↗	↗
F690/F740	↗	↘	0	→	0	0	0	→	↗	→	→
F440/F520	0	0	0	↘	→	↘	→	0	→	0	0


Thank you!
Contact
www.ceop-aegis.org