How to remove clouds in a time series of SST images?

Application to the Canary Island – Madeira Region

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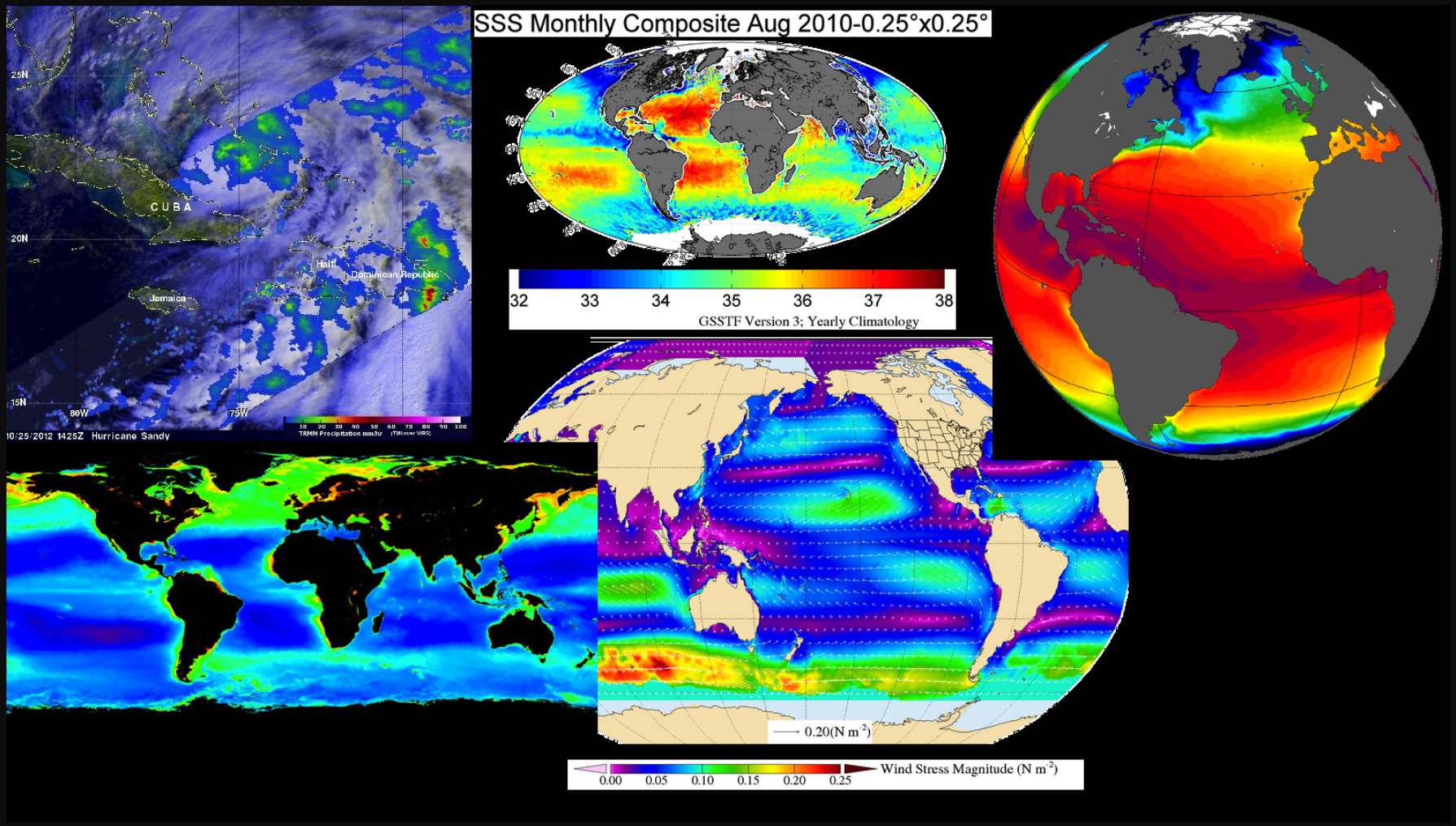
Satellites measure a lot of parameters, but . . .

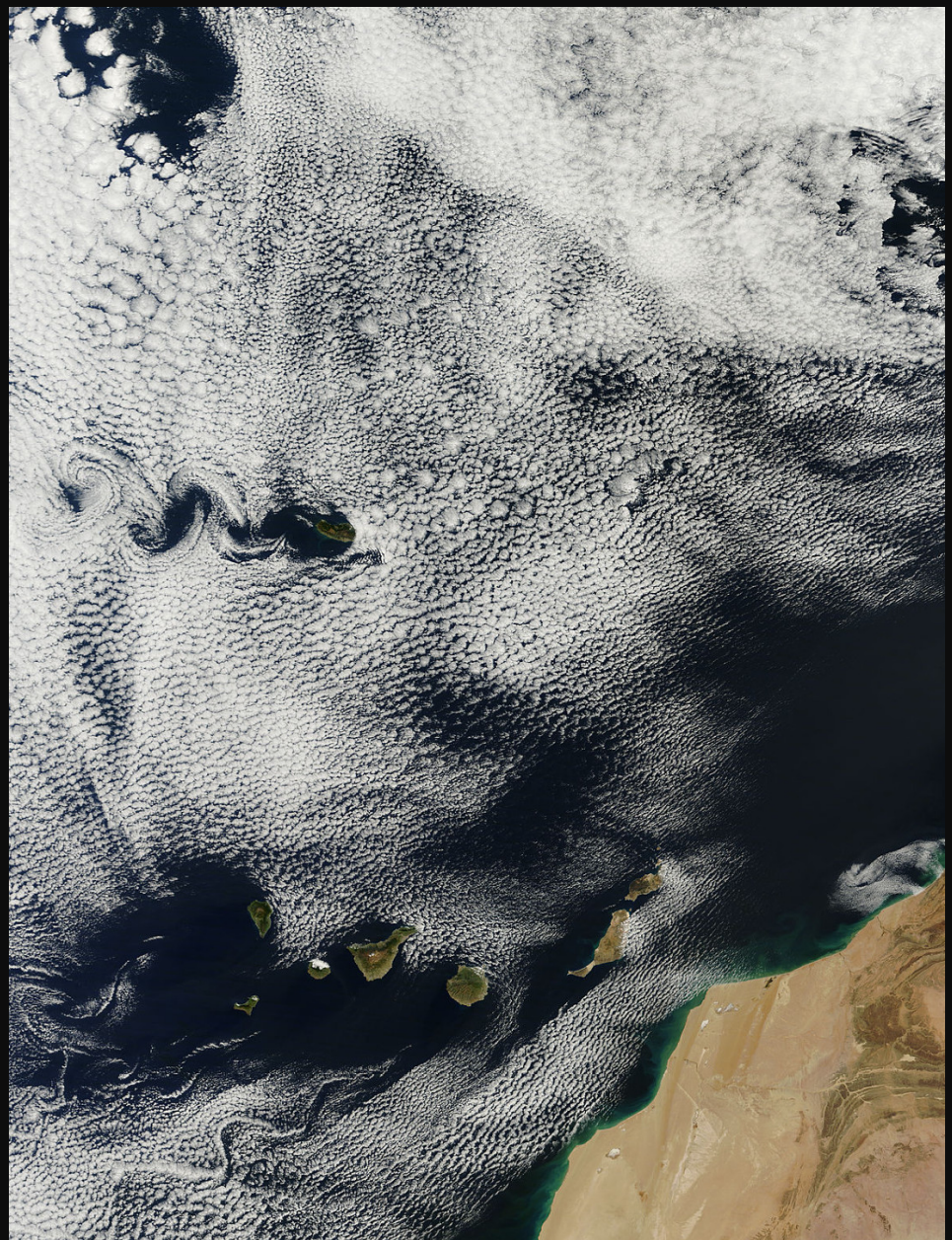


. . . they are limitations:

1. Spatial/temporal resolutions
2. Measurements limited to surface
3. Cannot view through clouds, dust, smoke, . . .

Small-scale processes in the studied region

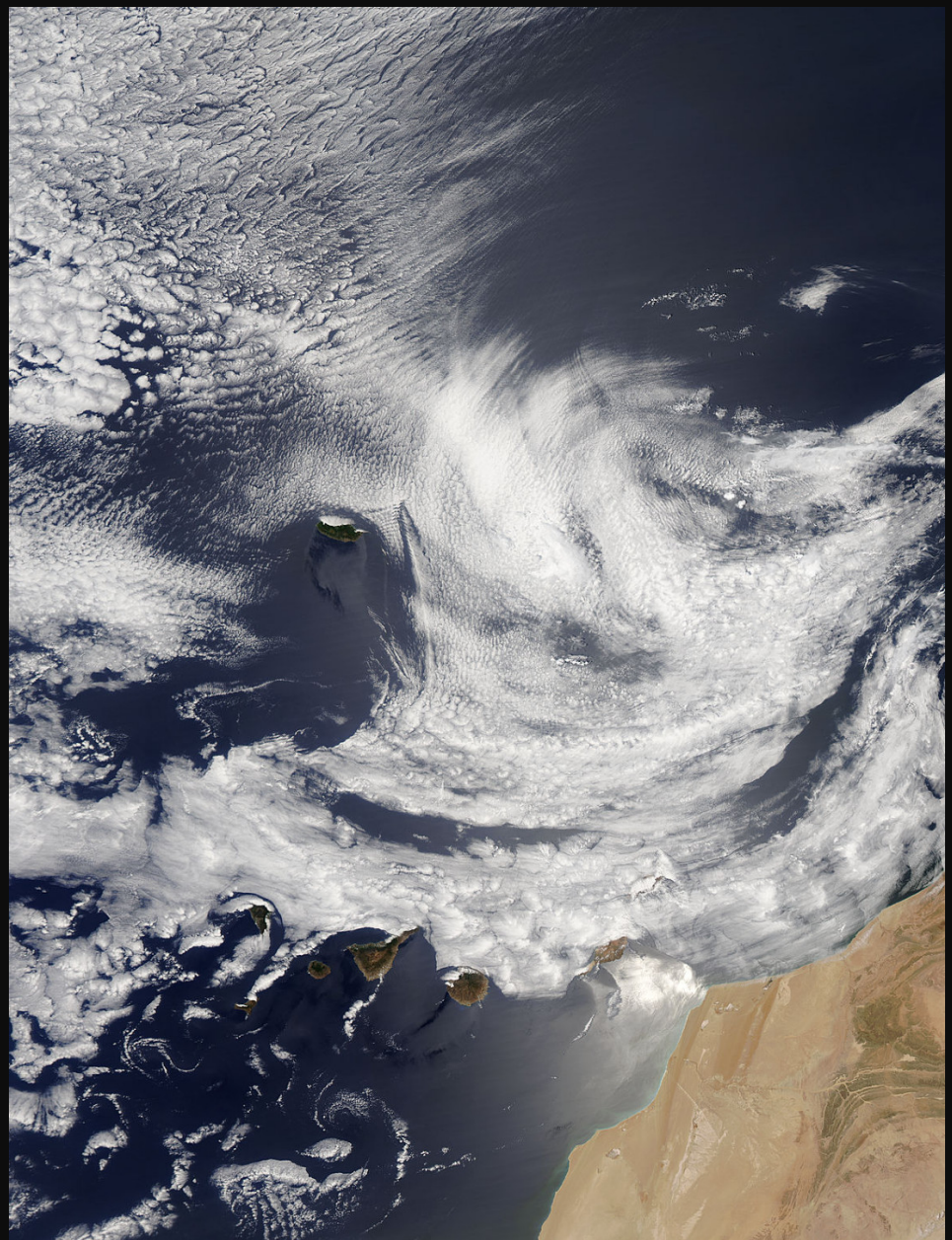
Eddies



MODIS-Terra
February 22, 2011

Small-scale processes in the studied region

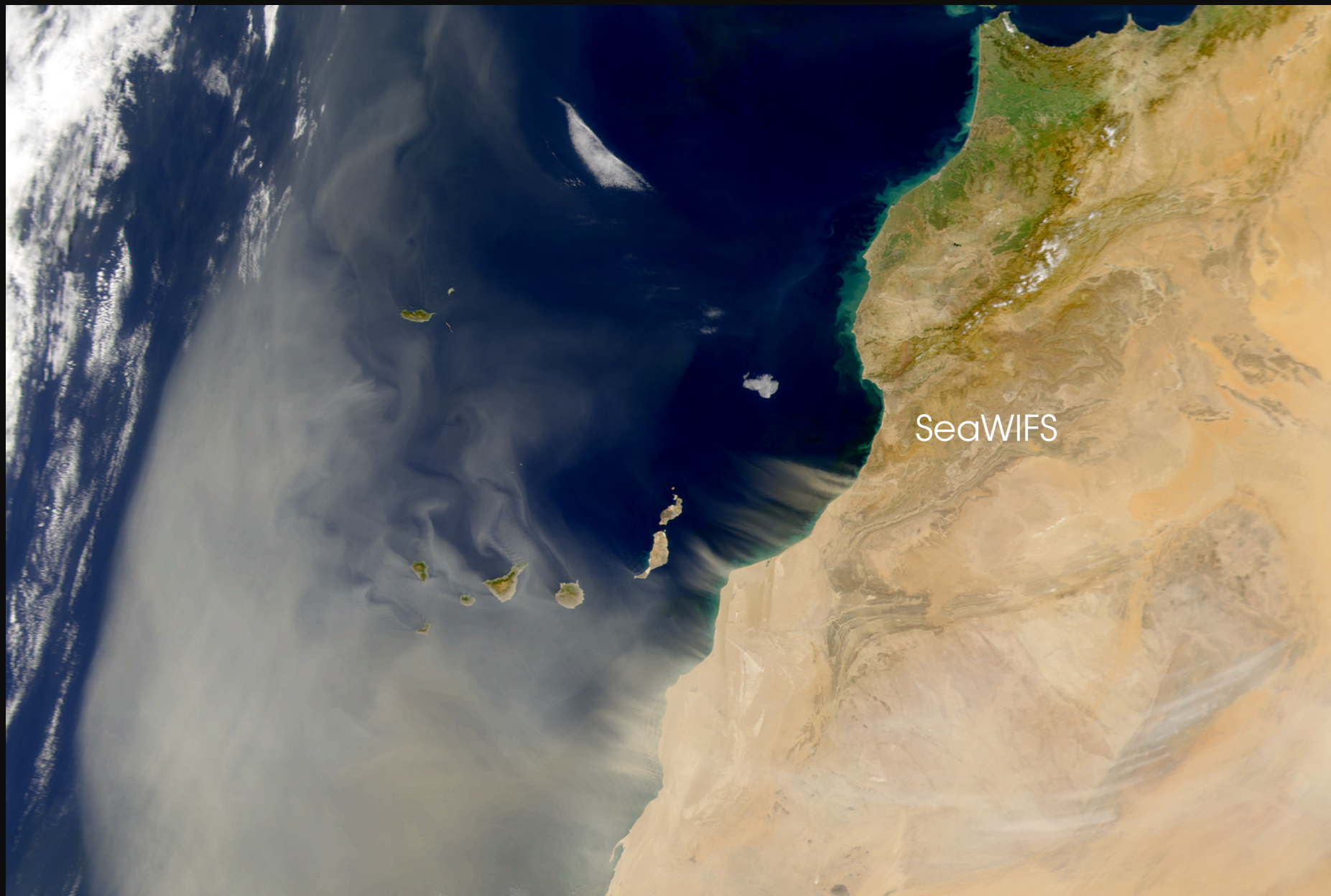
Island wakes



MODIS-Aqua
June 3, 2010

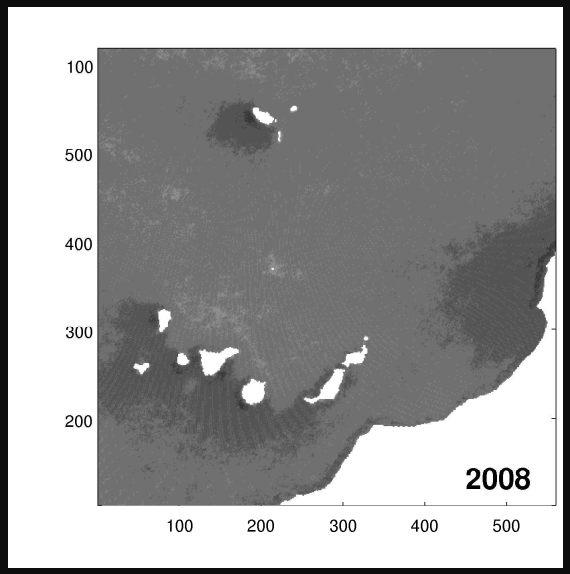
Small-scale processes in the studied region

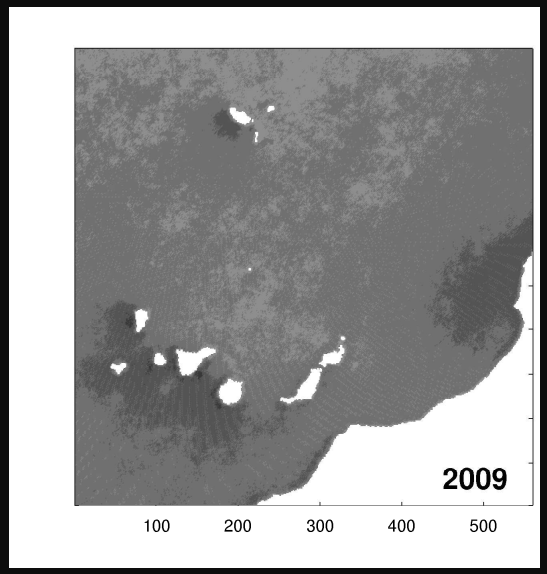
Dust input

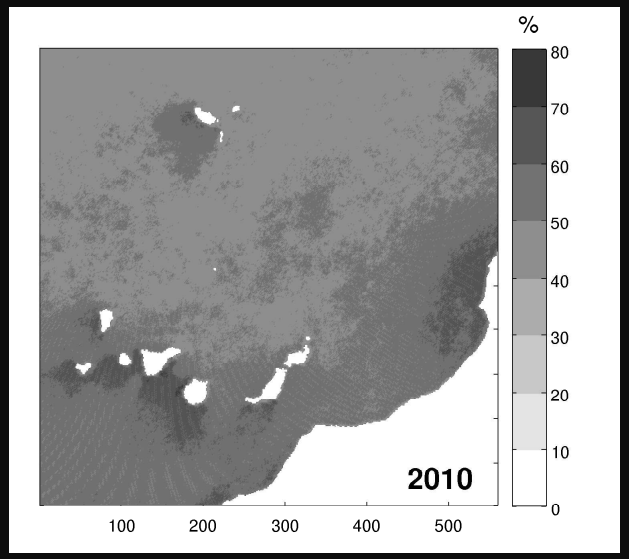


Application: SST

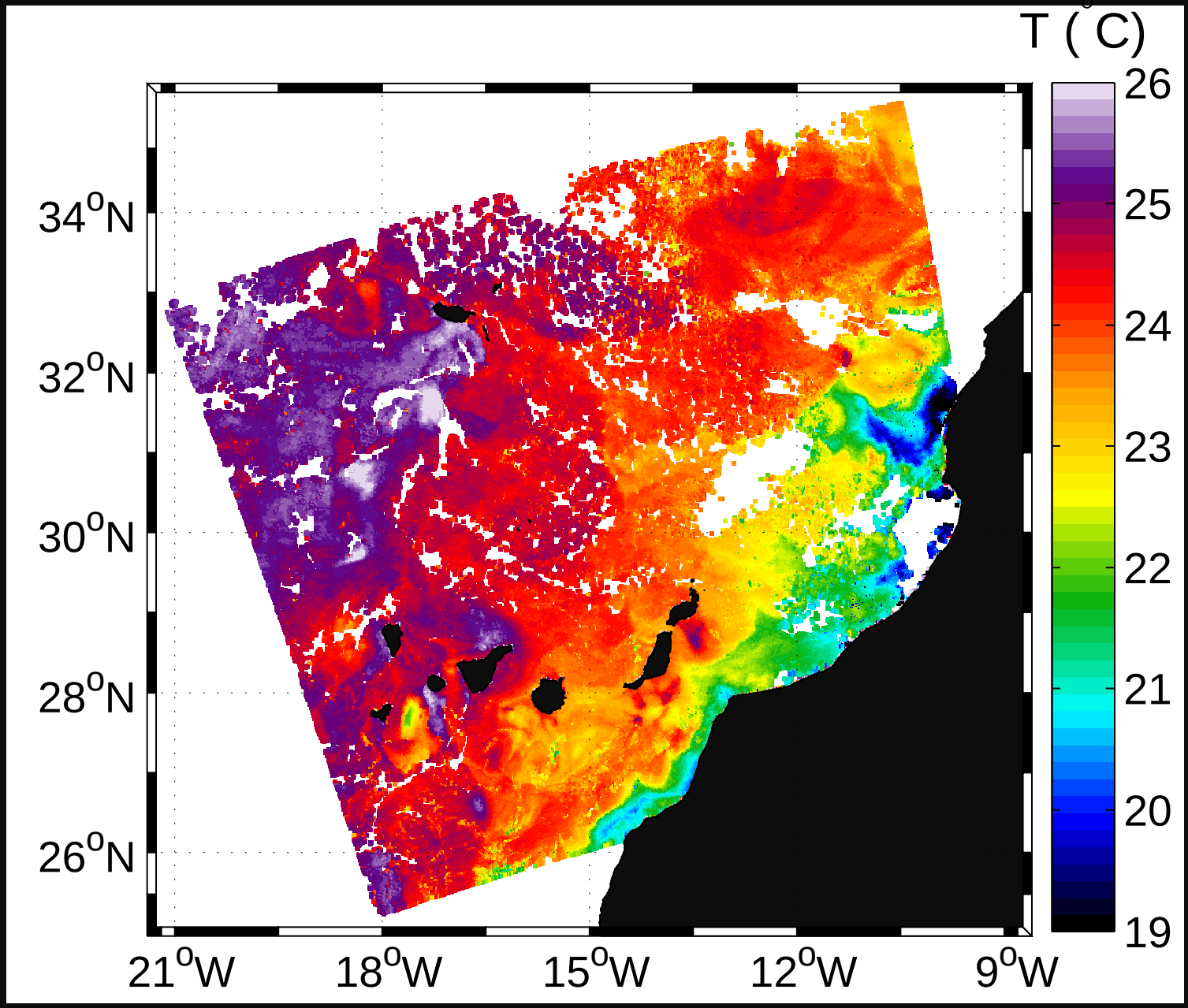
- Data (level 3): *http://www.medspiration.org*
- Night-time only
- Images with $> 5\%$ of valid pixels



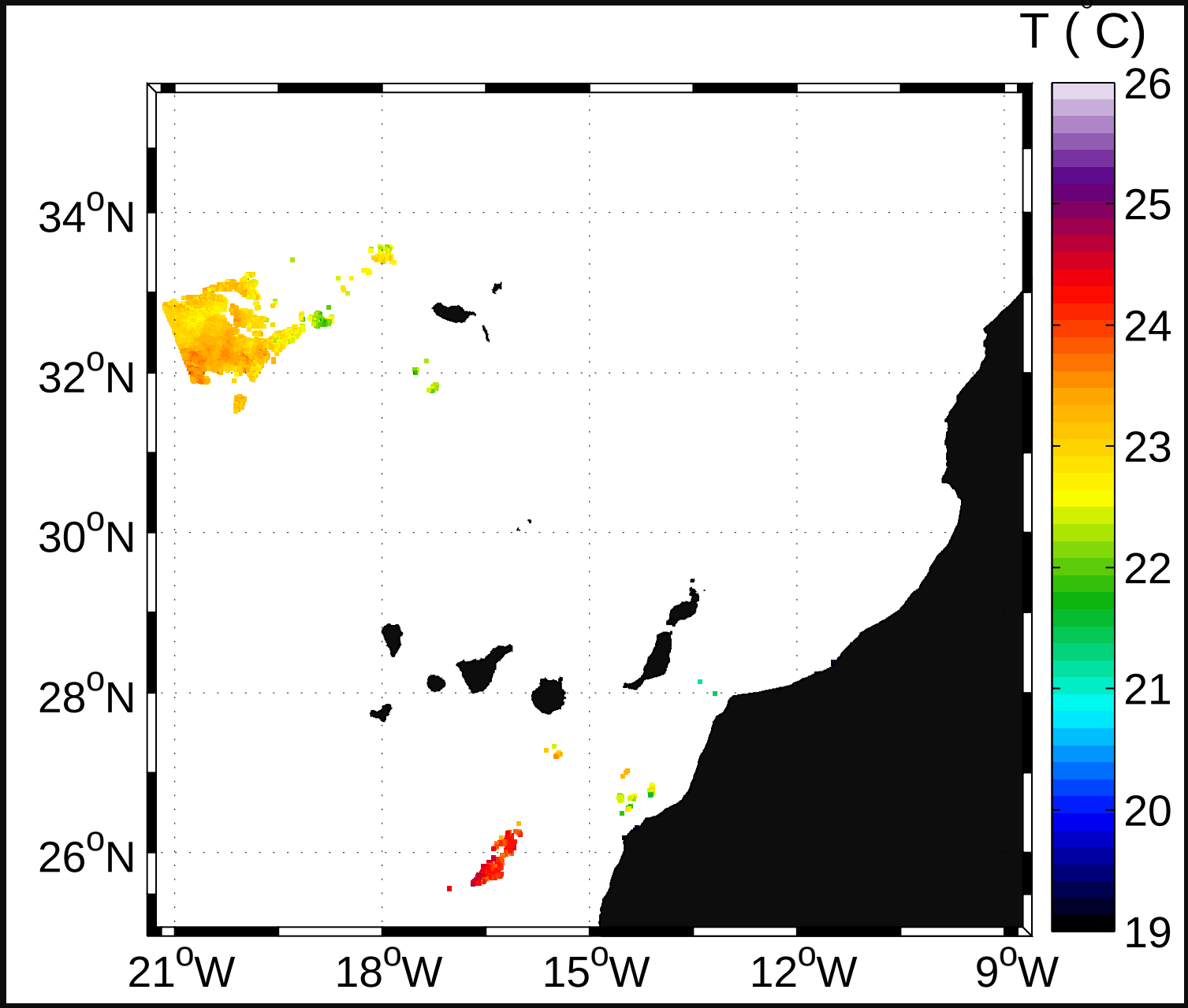




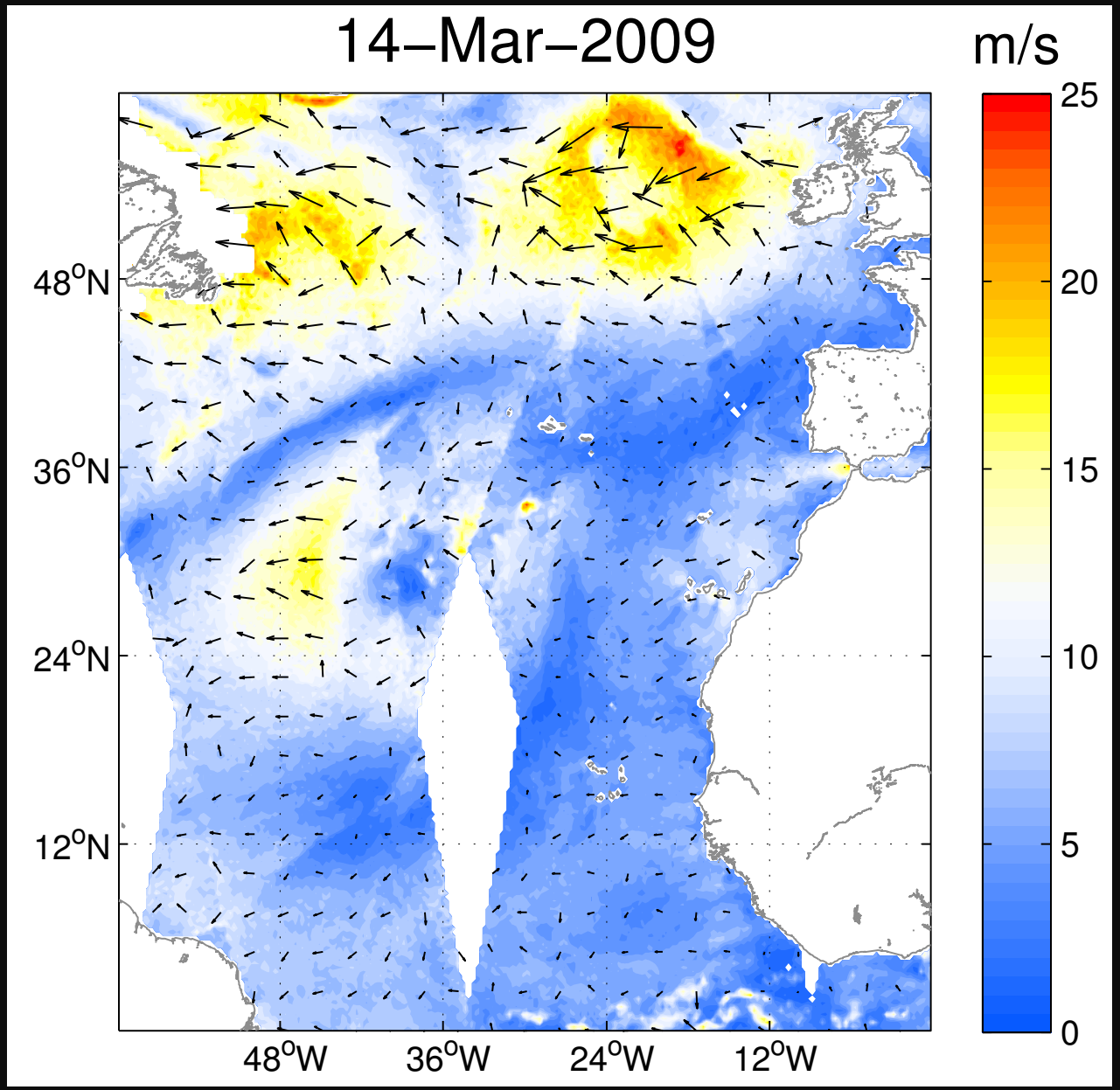
Examples



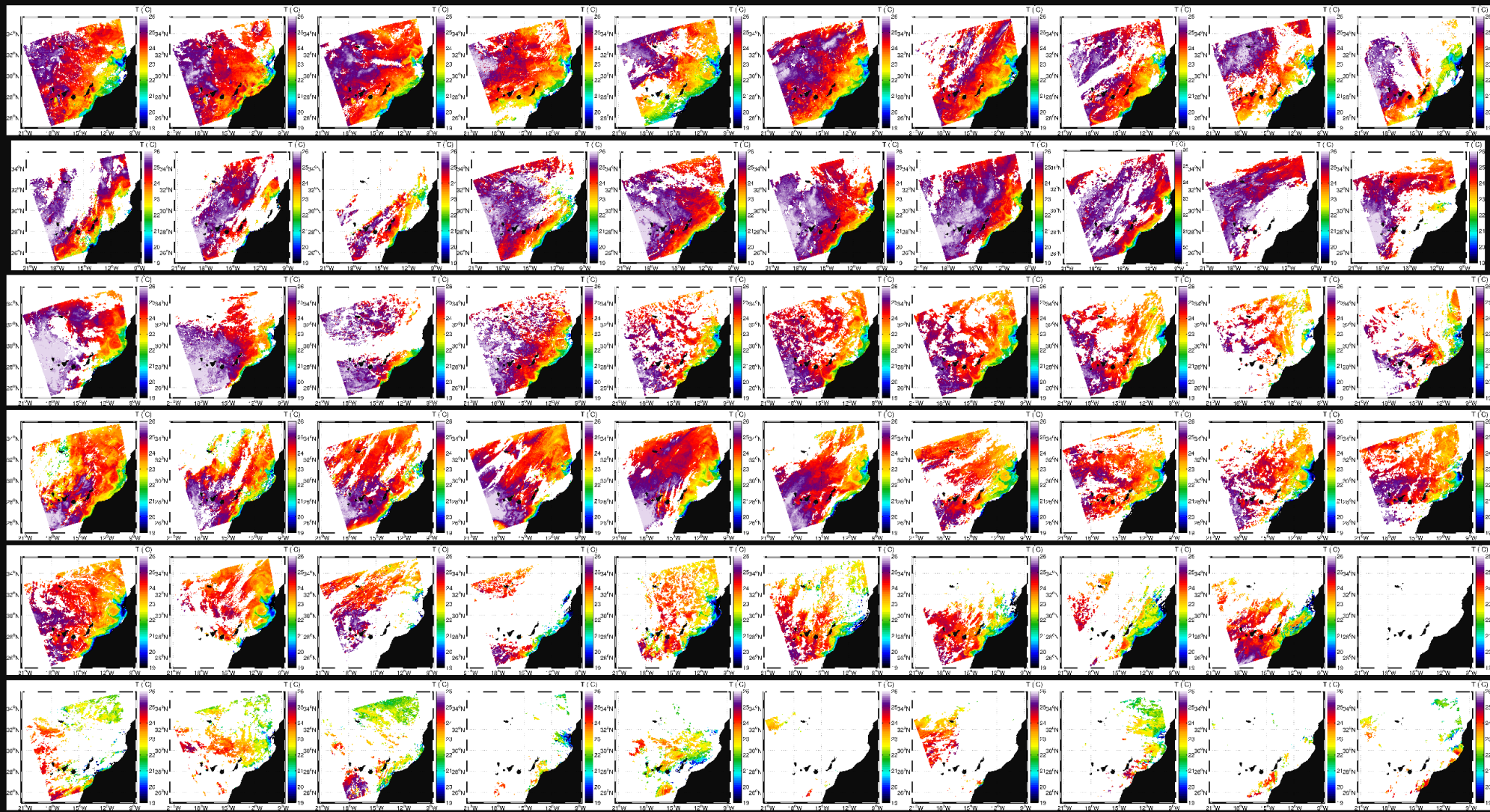
Examples



Examples



Solution: Use information from other images



A little bit of mathematics . . .

DINEOF =
Data INterpolating
Empirical Orthogonal Functions
(Beckers and Rixen, 2003, Alvera-Azcárate et al., 2005)

$$\mathbf{X} = \mathbf{USV}^T \tag{1}$$

with

$\mathbf{U}$	$\rightarrow$ *spatial EOFs*	$m \times N$
$\mathbf{V}$	$\rightarrow$ *temporal EOFs*	$n \times N$
$\mathbf{S}$	$\rightarrow$ *singular values*	$N \times N$

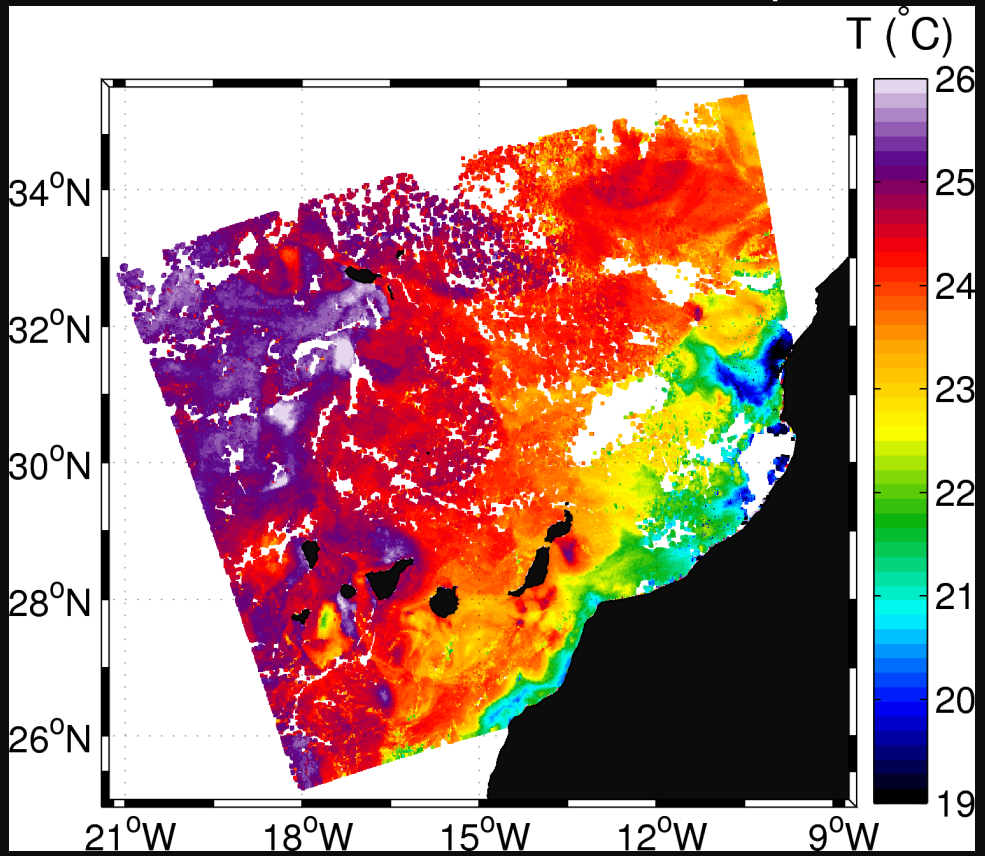
A little bit of mathematics . . .

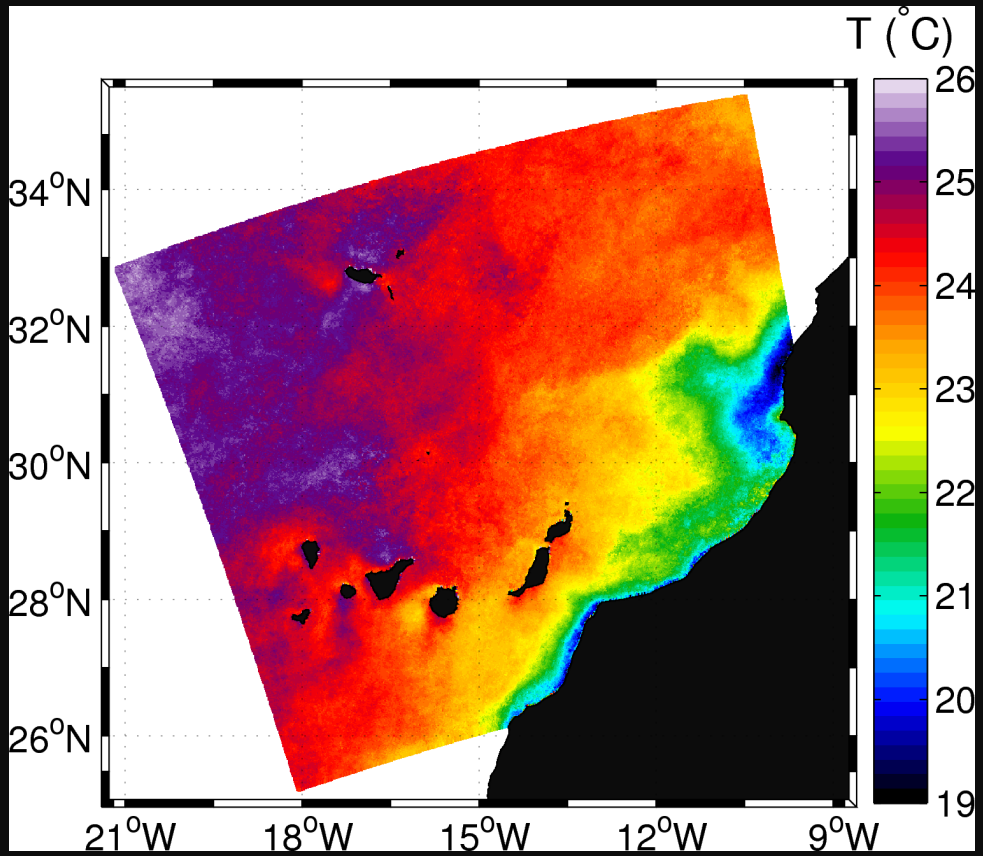
Iterative method

1. Start with $N = 1$ $\mathbf{X^1} = \mathbf{U^1 S^1 V^{1^T}}$
   1. Compute new values at missing pixels
   2. Repeat until convergence
   3. Estimate reconstruction error
2. $N = N + 1$ and repeat procedure
3. . . .
4. Final reconstruction: find $N = N_{opt}$ that minimises error

Results

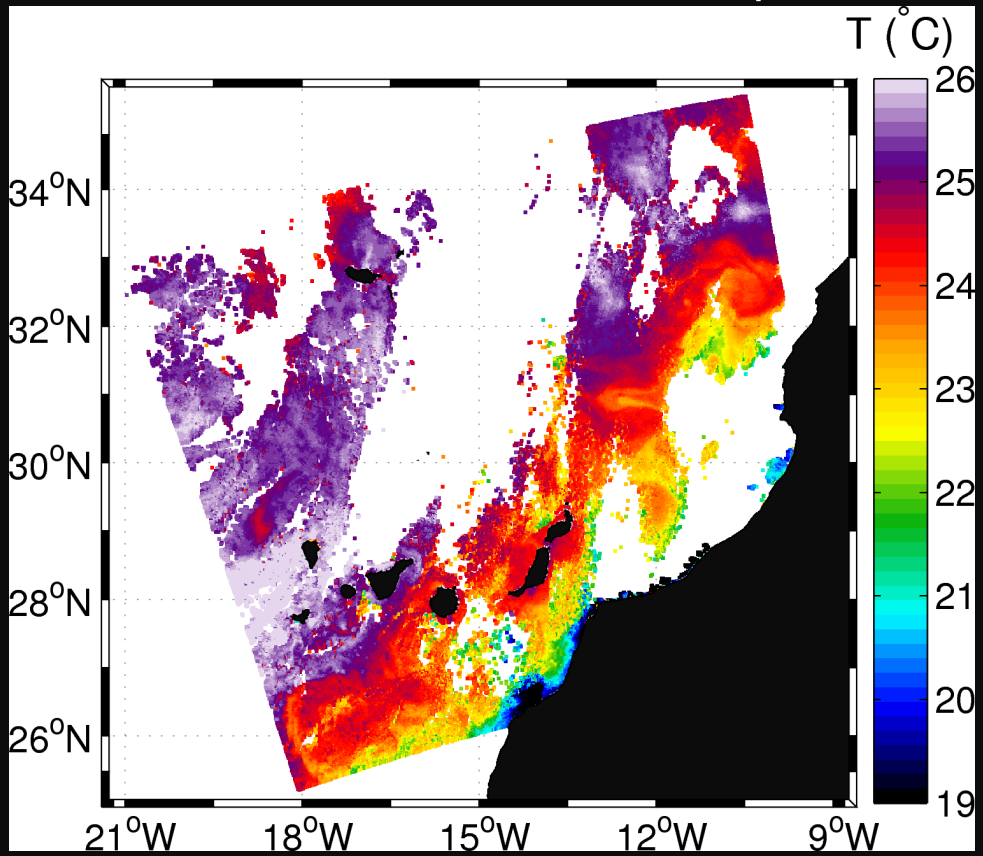
September 5, 2012

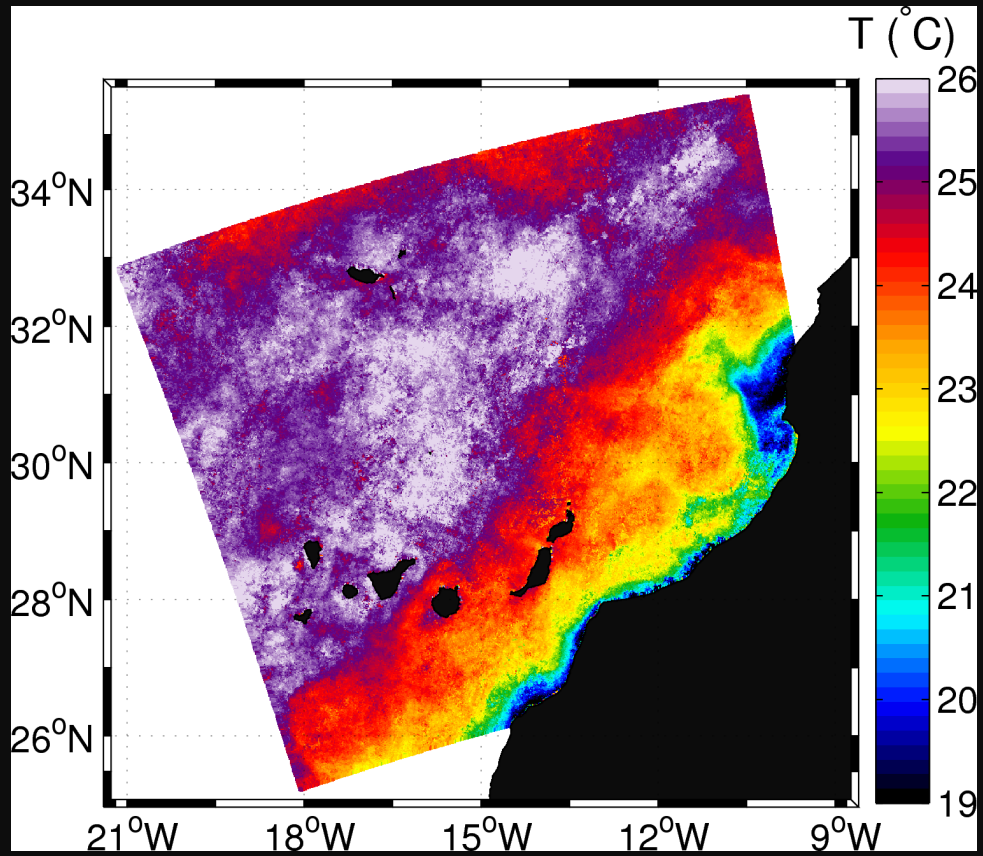




Results

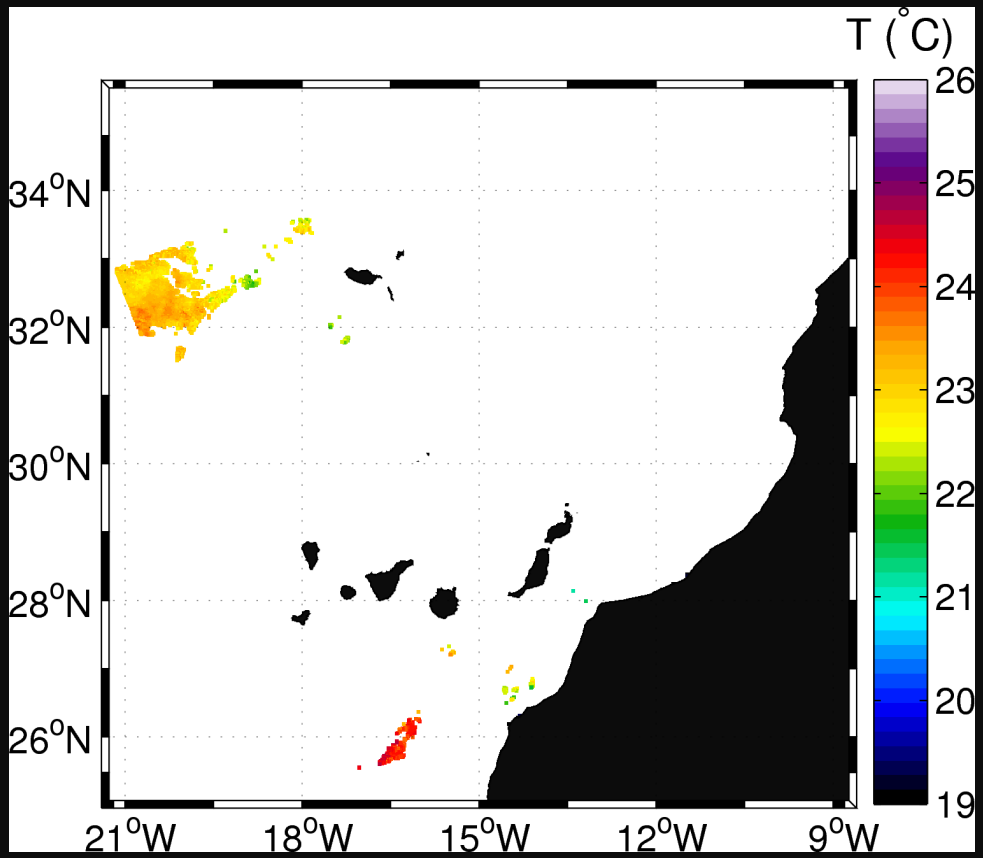
September 15, 2012

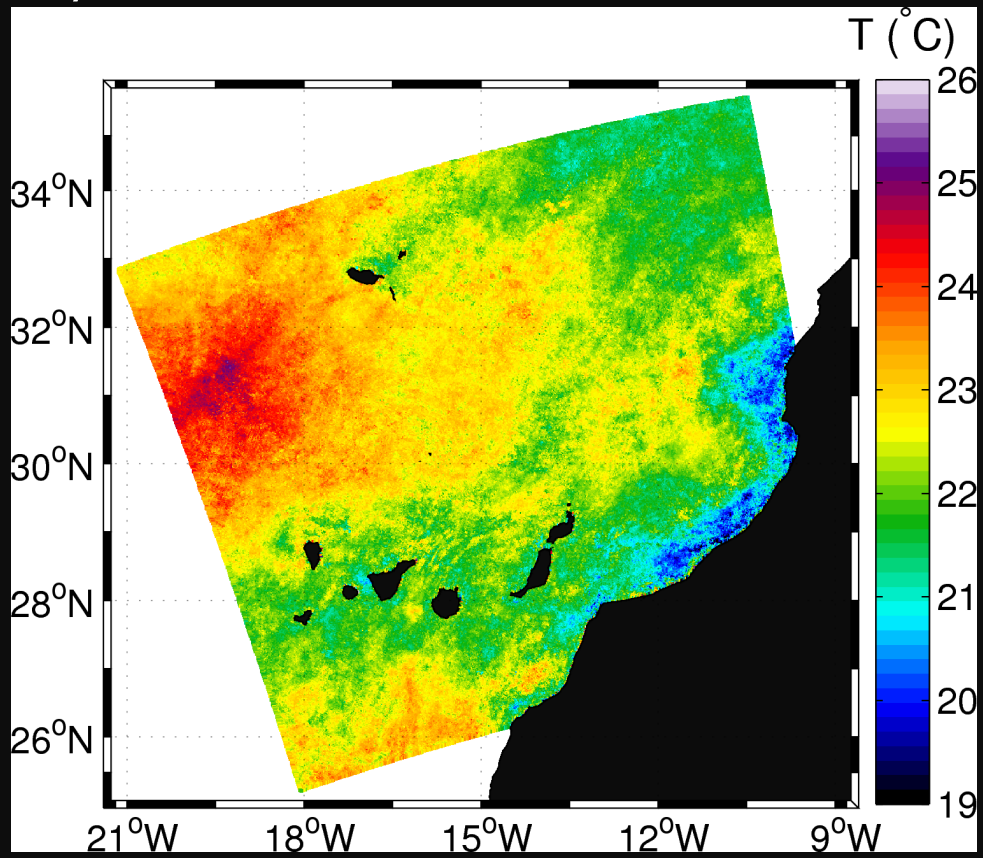




Results

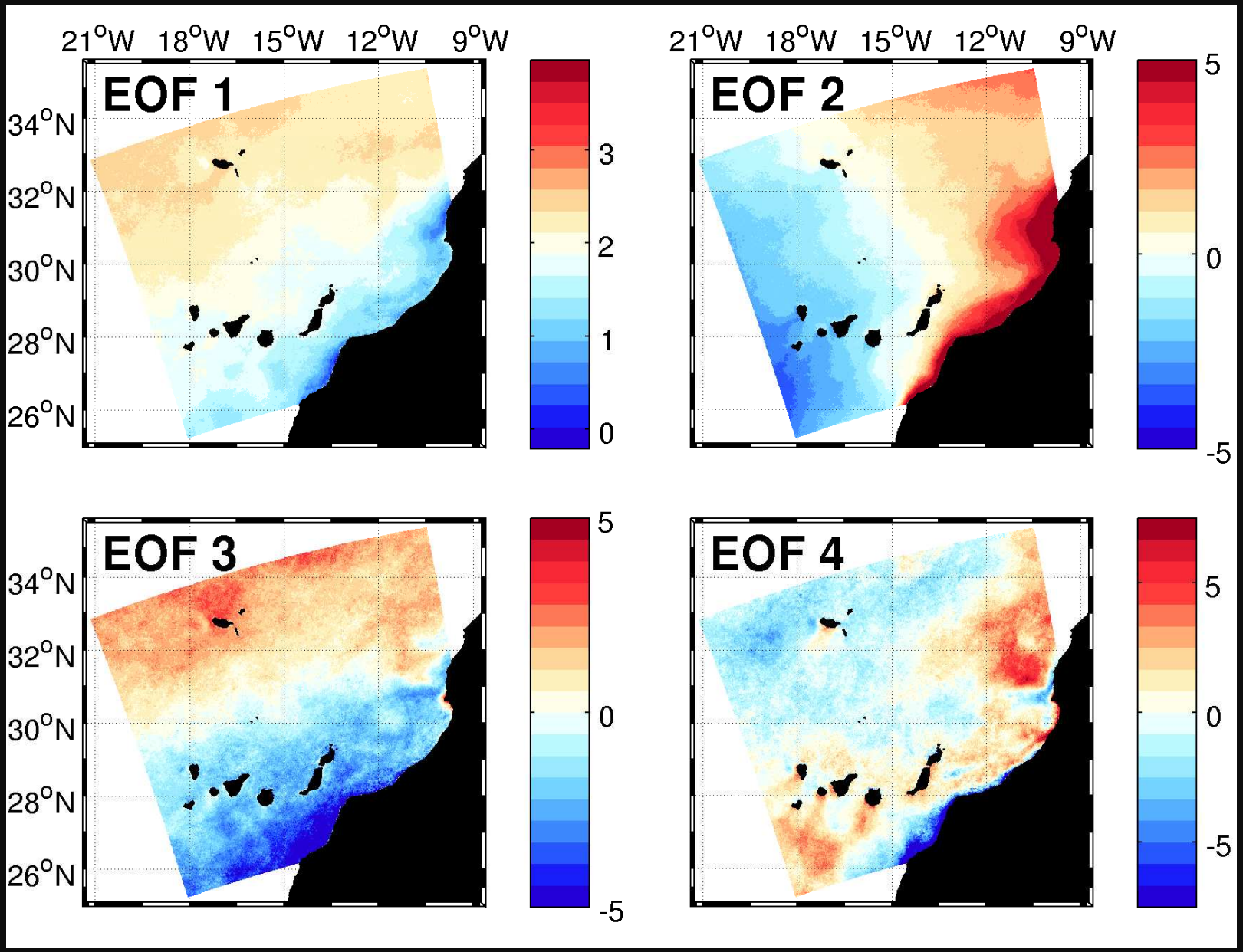
October 30, 2012





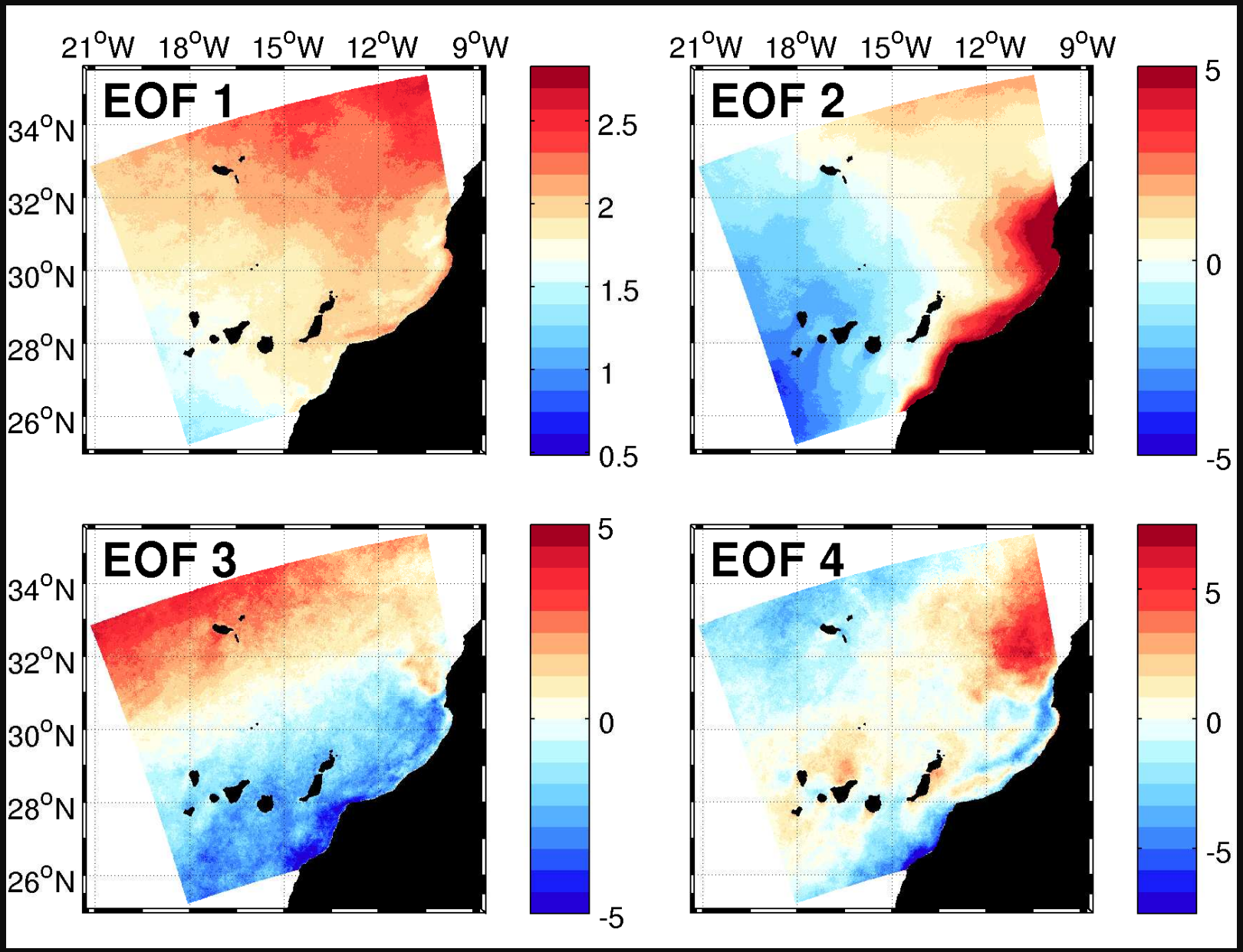
Spatial modes

2008



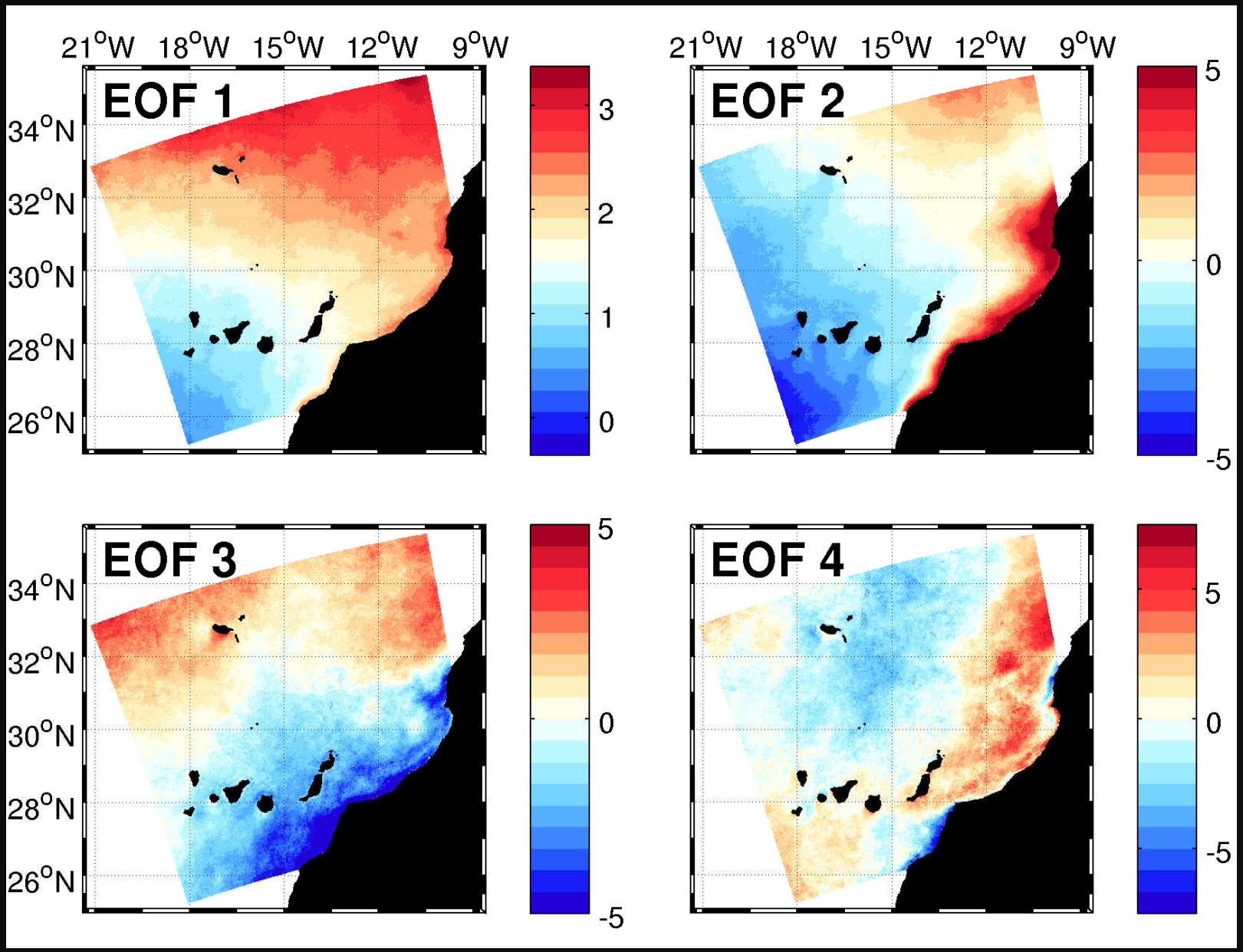
Spatial modes

2009

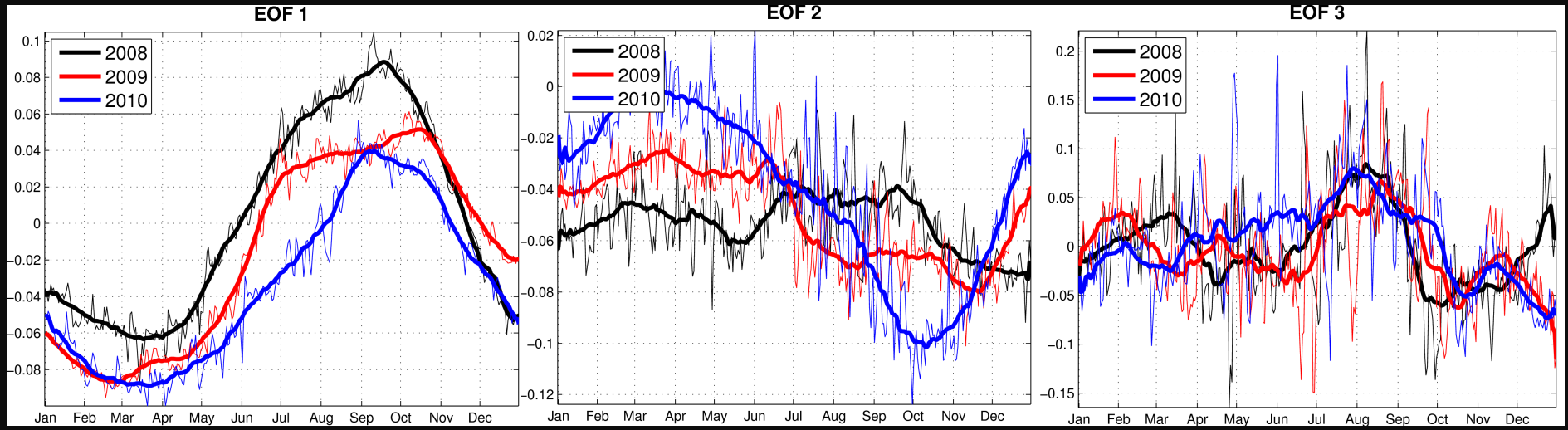


Spatial modes

2010



Temporal modes

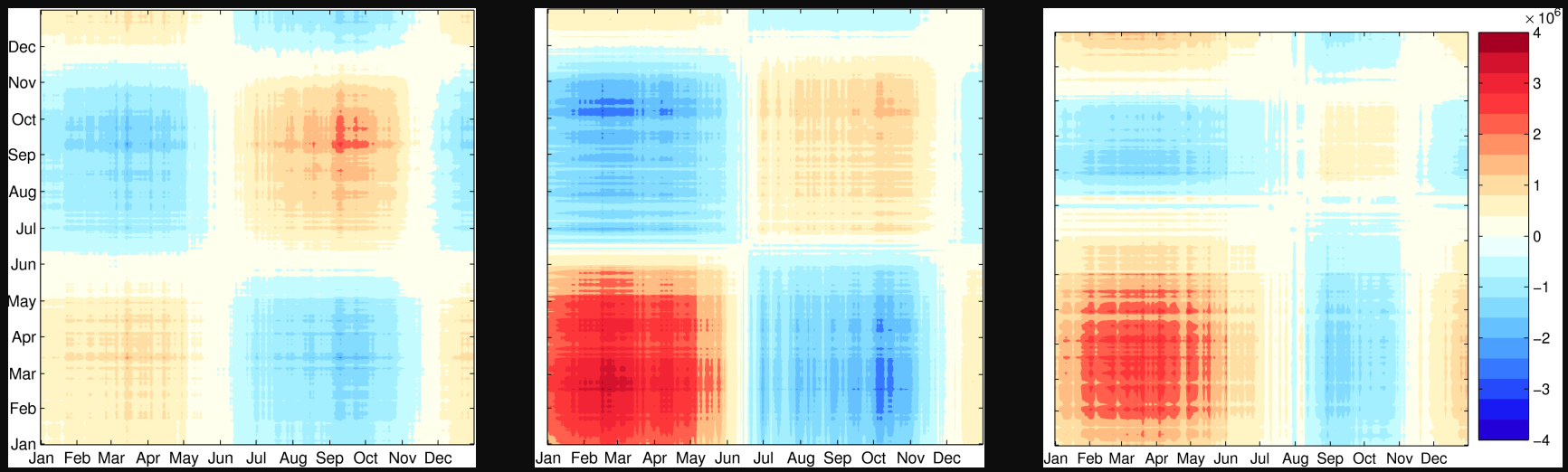


Improvement: smoothing temporal covariance

- $\mathbf{X} = \mathbf{U}\mathbf{S}\mathbf{V}^T$ decomposition
  $\mathbf{B} = \mathbf{X}^\mathbf{T}\mathbf{X}$ time covariance
  $\mathbf{B} = \mathbf{F}^\mathbf{T}\mathbf{B}\mathbf{F}$ filtering

$\rightarrow$ Coherence in time between close images
(Alvera-Azcárate et al., 2009)

2008 2009 2010

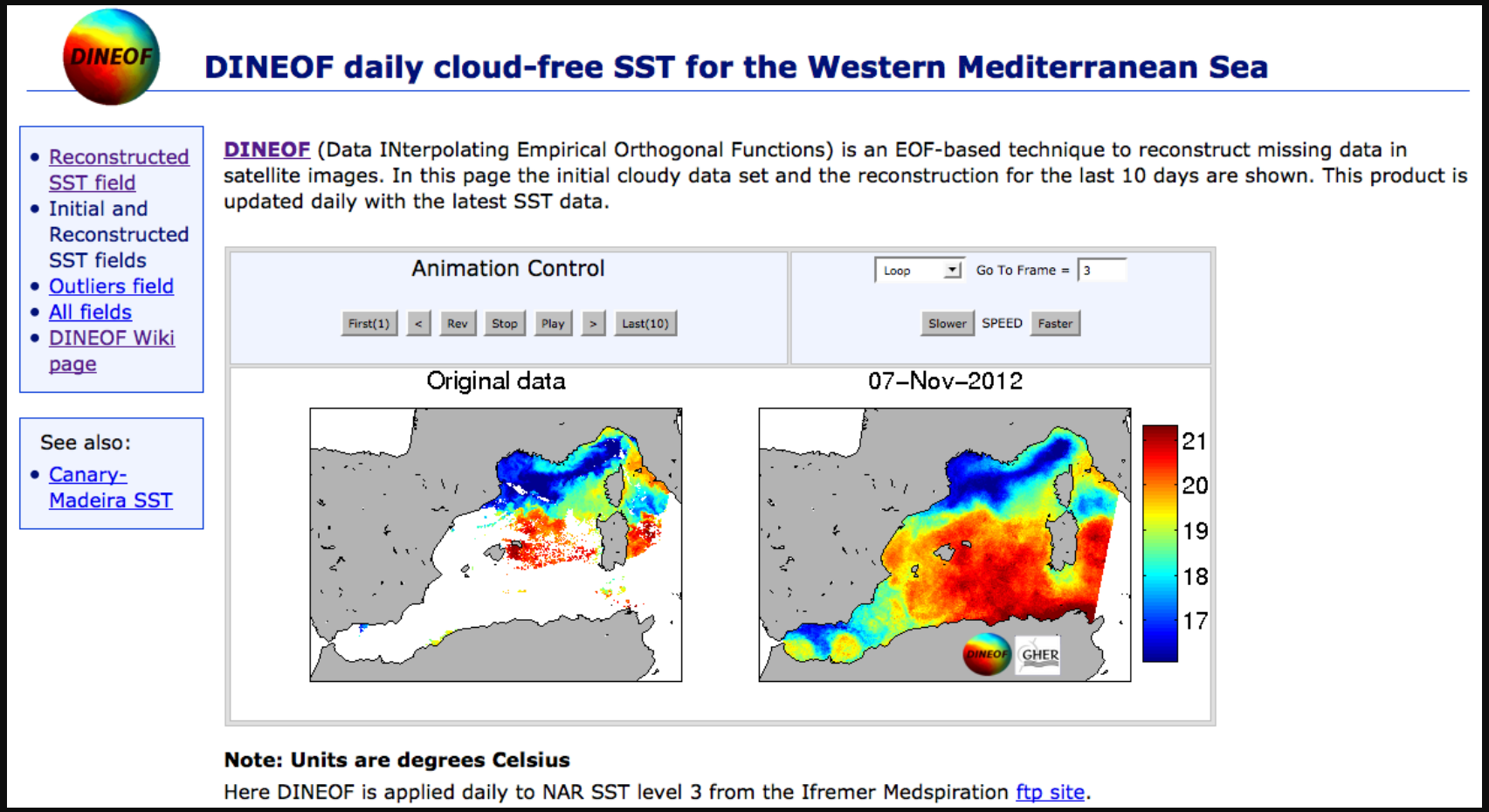


diagonal = variance with respect to mean

off-diagonal = covariance of one image with the others

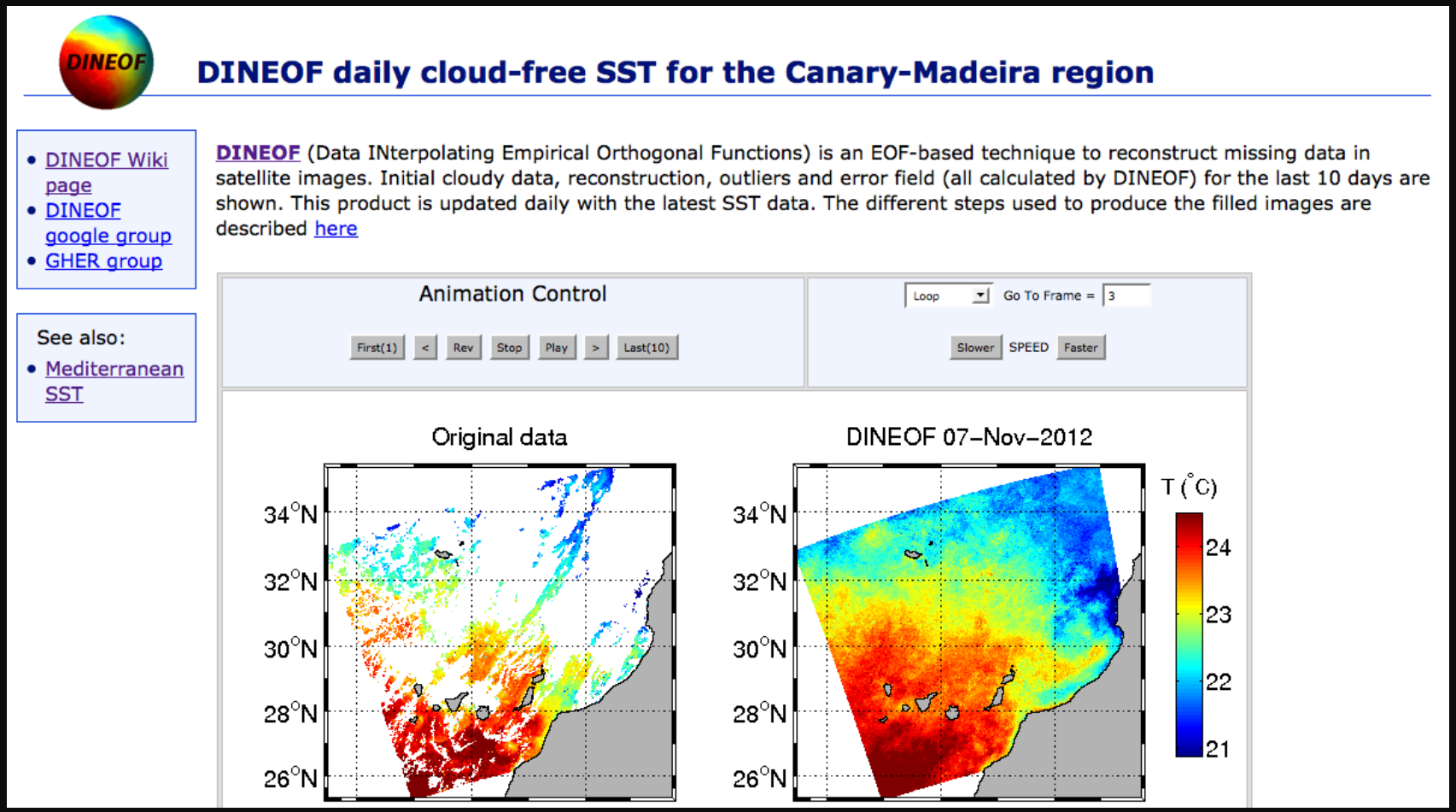
Automatic processing

http://gher-diva.phys.ulg.ac.be/DINEOF/dineof.html



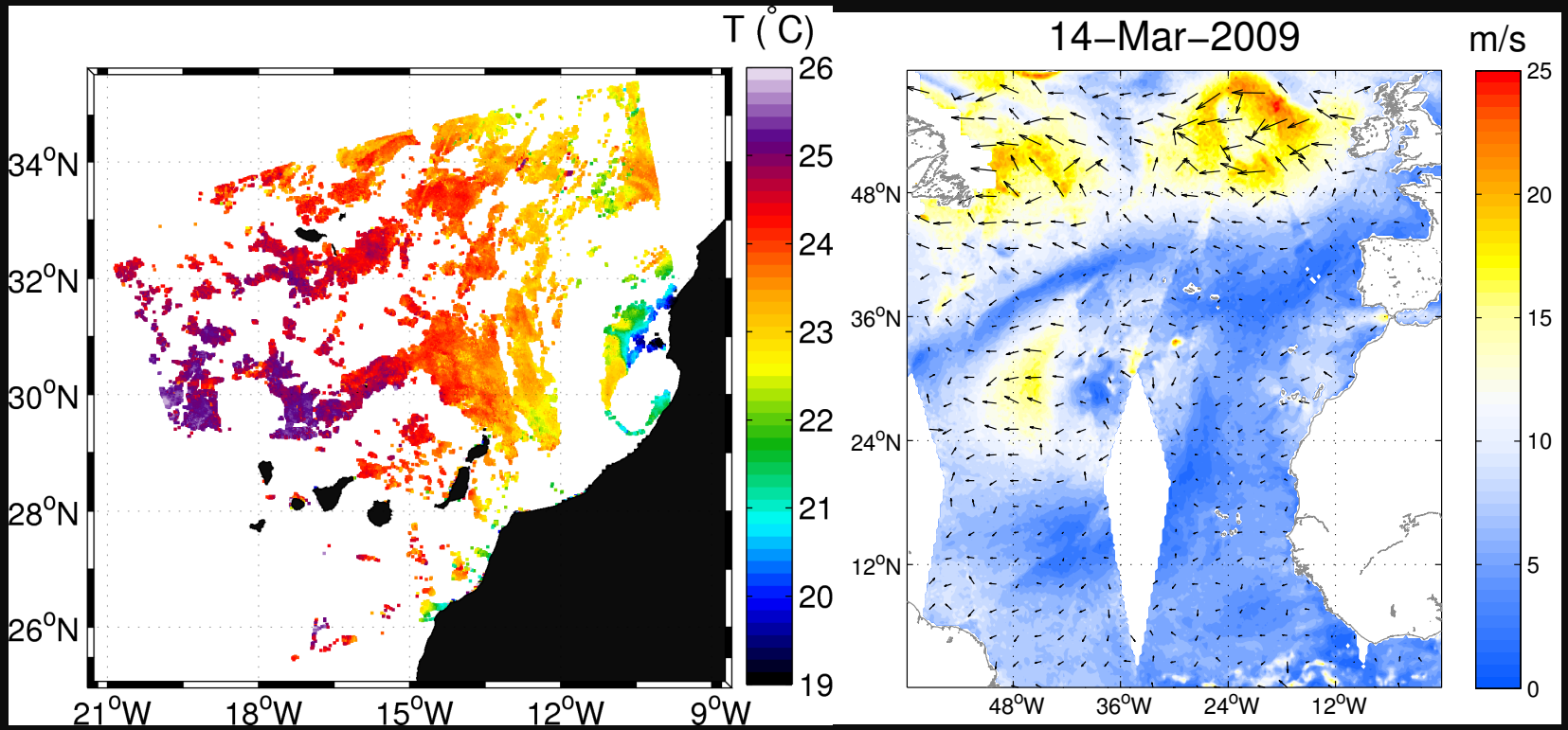
Automatic processing

http://gher-diva.phys.ulg.ac.be/DINEOF/dineof_allCAN.htm



What's more?

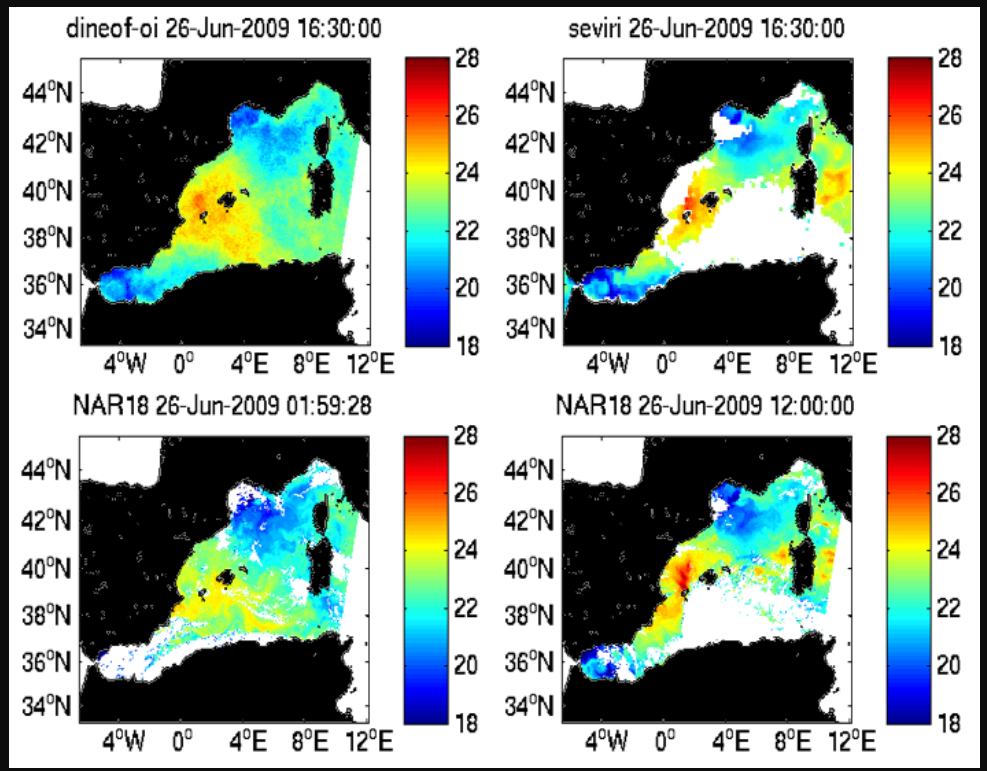
Multivariate analysis



SST + wind

What's more?

Merging data sets	polar-orbiting ↓	+	geostationnary ↓
Spatial resolution	2 km		10 km
Temporal resolution	12 hours		3 hours



What's more?

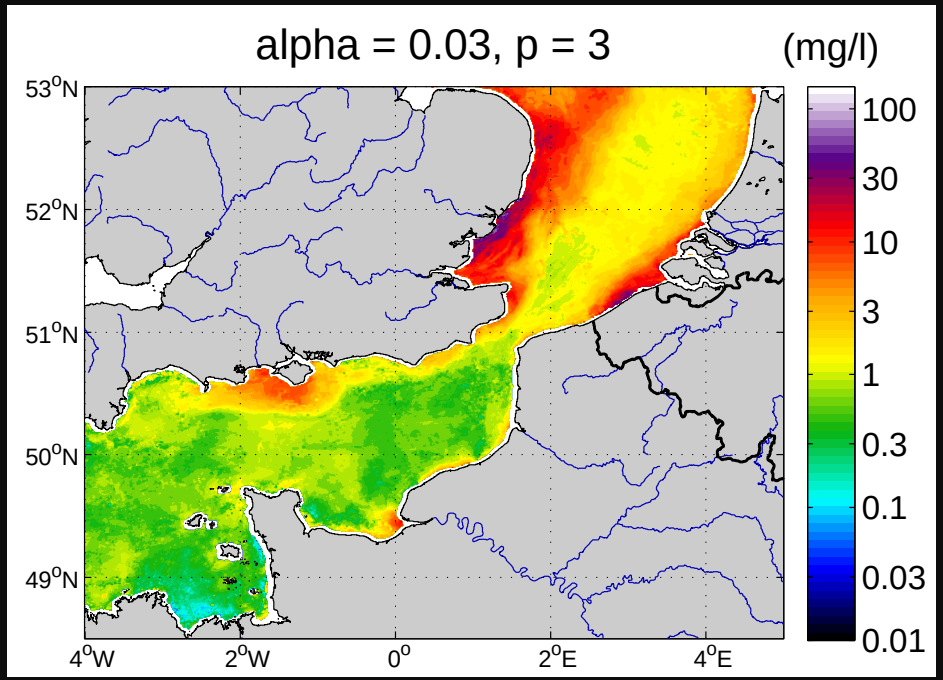
DINEOF: remote-sensing measurements + model variables

↓ ↓

no explicit parameterization

forecasts

"Forecast" of Total Suspended Matter



Conclusions

How to remove clouds in satellite images?

- Use the recurrence of information
- Combine relevant parameters
- Merge different satellites
- Exploit numerical model


Thanks for you attention