Enhanced resolution of SST fields from gradient transformation

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Motivations

Numerous small features (eddies, filaments, sharp fronts, ...) revealed by high resolution satellite images ($\sim$ 1-10 km) of SST or chlorophyll.

Small scales make a significant contribution to the horizontal and vertical transport in the upper oceanic layers (*Lapeyre & al. 2006, Capet & al. 2008, Klein & al. 2008*)

With regard, more specifically, to SST fronts :

- interactions of sharp SST gradients and the marine atmospheric boundary layer and deeper atmosphere
- major contribution in methods aiming to retrieve or improve horizontal and vertical velocities in the upper ocean from surface data

Motivations

We are provided with :

- what we call here low resolution (LR, $\sim$ 60 km) SST observations with a global and quasi daily coverage
- discontinuous high resolution (HR, $\sim$ 1-5 km) SST observations that are valid only for clear-sky conditions
- Gap-free L4 SST products : commonly used interpolation methods, such as optimal interpolation, are based on gaussian field assumptions, with correlation scale of the order or larger than the first Rossby radius, that are not suitable to restitute thin and elongated sharp structures.

We are also provided with global satellite altimetry maps capable of resolving mesoscale structures (*Morrow et al. (2012)*).

Possible approach to generate finer scale relies on transport processes (*Desprès et la. (2011), Dencausse et al. (2014), Berti et al. (2014)*).

Objective

Objective of this study

Characterization of high resolution SST fields ($\sim$ IR products resolution) with repect to low resolution fields ($\sim$ MW products resolution), i.e high resolution spatial distribution with repect to low resolution fields

$\Rightarrow$ Investigate the enhanced resolution of SST fields from an Eulerian technique relying on a priori-defined relationships between LR and HR images.

Outline

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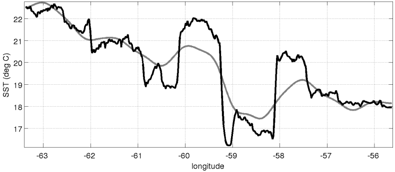
Dataset

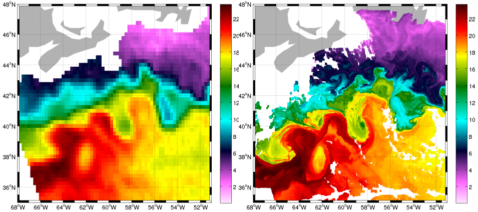
AMSR-E / MODIS dataset

SST fields simultaneaously observed by MW and IR instruments :

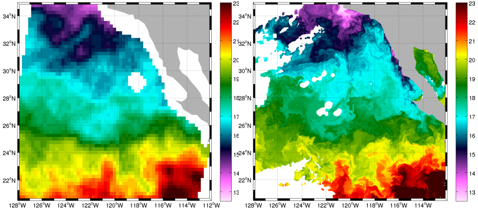
- Grids : 0.25° (AMSR-E), 0.02° (MODIS)
- MODIS SST images destriped (*Bouali and Ignatov (2014)*)



MODIS (black curve) and AMSR-E (gray curve) SST transect at latitude 39.125° N over the Gulf Stream area



AMSR-E and MODIS SSTs on 6 Mai 2010 over the Gulf Stream



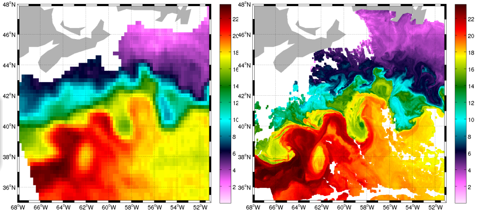
AMSR-E et MODIS SSTs on 29 March 2010 off South California

HR / LR filtering approximation

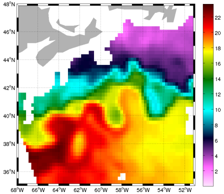
Low-pass filtering approximation

Filtering estimation :

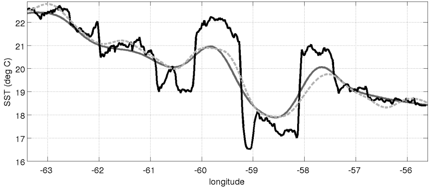
⇒ Smoothing filter : ∼ 60 km averaging filter or Gaussian filter with a standard deviation of 22 km



SST AMSR-E and MODIS on 6 mai 2010



SST from MODIS smoothed with a Gaussian filter ($\sigma = 22km$) and sampled on the LR grid



SST section from AMSR-E (light gray) upsampled on the high resolution grid, MODIS (black) and MODIS SST smoothed with a Gaussian filter, $\sigma = 22km$ (gray)

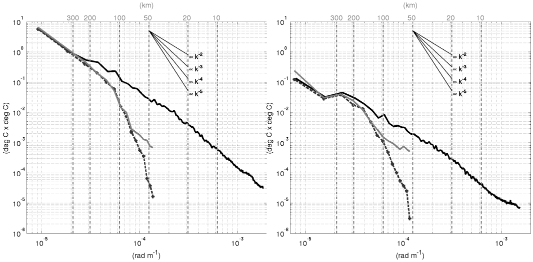
Outline

Spectral characterization

Spectral analysis

- Variance distributions impacted by the spatial filtering for scales smaller than 200-250 km
- In the 70-250 km band, MODIS SST spectral slopes close to -2, AMSR-E spectral slopes close to -4

$\Rightarrow$ Spatial filter acting as a $\propto k^{-2}$ filter in the Fourier domain

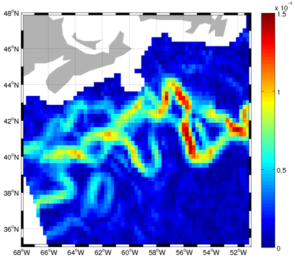


2D spectra from MODIS SST (solid black line), AMSR-E SST (solid grey line) and smoothed (by a Gaussian filter with a standard deviation of 22 km) MODIS SST (dash-dot black line). For comparison the straight lines indicate -2, -3,-4 and -5 spectrum slopes.

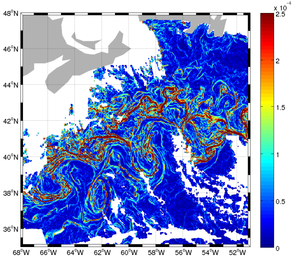
SST anomalies and gradients

High resolution SST gradient distribution

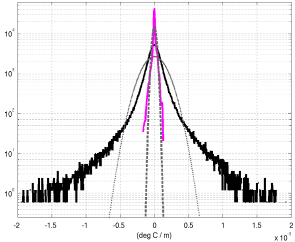
- Narrow et sharp gradient structures on high resolution images with higher gradient values ($\sim$ 10-12 times higher)
- The strongest gradients are visible (in a smoothed version) in the low resolution fields, the lowest having disappeared
- Large regions with small gradient values and small regions of high gradient values



AMSR-E SST gradient ($degC\,/\,m$)



MODIS SST gradient ($degC\,/\,m$)



Zonal SST gradient distribution

$\Rightarrow$ **High resolution gradient distribution far from Gaussian**

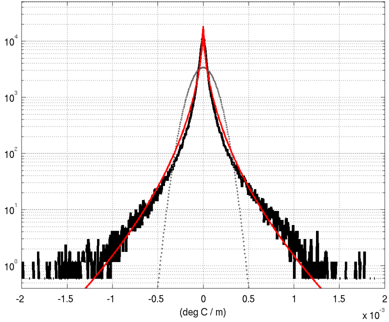
SST anomalies and gradients

High resolution SST gradient distribution

- Possible model for these heavy-tailed distributions : **Hyper Laplacian** *(Tappen, 2003, Frishnan and Fergus, 2009)*

$$g(x;\sigma,\lambda) = \frac{\lambda\alpha(\lambda)}{2\sigma\Gamma(\frac{1}{\lambda})} \exp\left\{\left[-\alpha(\lambda)\left|\frac{x}{\sigma}\right|\right]^{\lambda}\right\}$$

with the variable x, Γ the Gamma function, and $\alpha(\lambda) = \sqrt{\Gamma(3/\lambda)\Gamma(1/\lambda)}$ and $\lambda \sim \mathbf{0.5}$

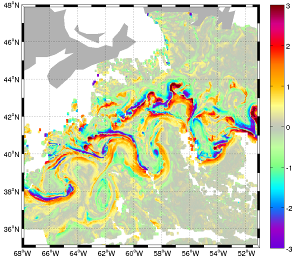


Normalized histogram of zonal SST gradient (black line) compared to the Gaussian distribution (dotted grey line). The red line is the hyper-Laplacian fit with $\lambda = 0.5$

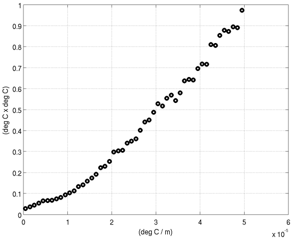
SST anomalies and gradients

Anomaly distribution

- Anomaly : MODIS SST minus smoothed MODIS SST (no large scale biases)
- Elongated and sharp structures highlighted
- Large regions with very low values and some regions with large anomalies yielding also to non-Gaussian distributions



SST anomaly (*degC*)



SST anomaly versus low resolution SST gradient

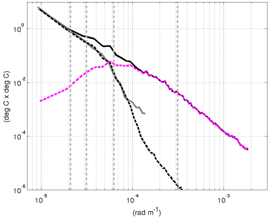
⇒ Non-Gaussian distributions
⇒ Relationship between anomaly and low resolution SST gradient

Outline

1. Introduction
2. Data
3. High resolution characterization tools
4. Reconstruction from gradient transformation
5. Conclusion

Introduction

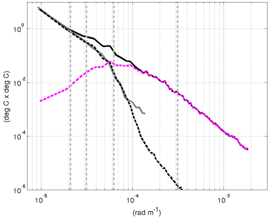
- For scales smaller than 250 km, loss of energy clearly shown by the spectral analysis



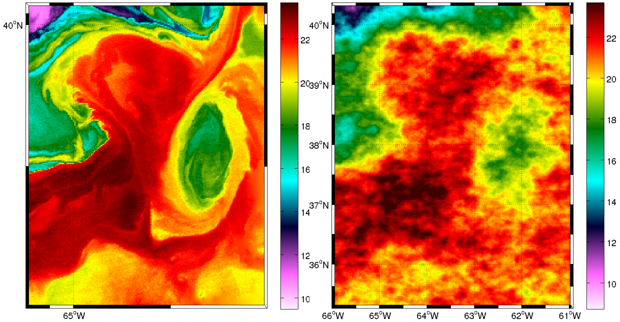
SST spectra : MODIS, AMSR-E, smoothed MODIS SSTs and anomaly (black, gray, dot gray, magenta)

Introduction

- For scales smaller than 250 km, loss of energy clearly shown by the spectral analysis
- But this characterization tool does not provide information concerning the spatial distribution of the small scales variability
  - Illustration : add the missing energy (to the LR field) with random phases



SST spectra : MODIS, AMSR-E, smoothed MODIS SSTs and anomaly (black, gray, dot gray, magenta)



Same spectra for these 2 images

Introduction

⇒ **Significant role of the phase information**

Proposition :

- Use the phase information provided by the low resolution field and estimate the contribution of the major fronts.

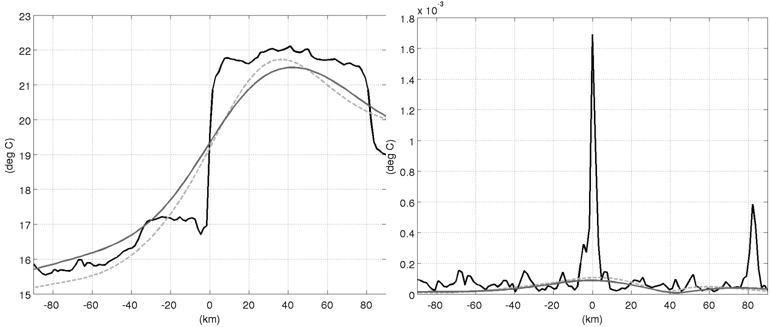
Method : enhanced resolution of SST fronts

- Propose a gradient profile model
- Estimate the transfert function between low and high resolution gradient profiles (on edge points)
- Construct the ≪ high resolution ≫ gradient field
- Reconstruct the ≪ high resolution ≫ SST field

Gradient profile and transfert function model

Gradient profile model

Example of SST and SST gradient profiles



SST and SST gradient profiles from MODIS (black), AMSR-E (dot gray), MODIS smoothed SSTs.

Gradient profile and transfert function model

Gradient profile model

$$g(x;\sigma_i,\lambda) = \frac{\lambda\alpha(\lambda)}{2\sigma_i\Gamma(\frac{1}{\lambda})} \exp\left\{\left[-\alpha(\lambda)\left|\frac{x}{\sigma_i}\right|\right]^{\lambda}\right\}$$

First approach : $\lambda = 2$

$$p_i(x;x_0) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{d(x,x_0)^2}{2\sigma_i^2}}$$

with i for low or high resolution, x_0 edge point, $d(x,x_0)$ distance from x_0 in the gradient direction

Transformation of low resolution profiles to high resolution profiles
Given $I_l(x,y) = G(x,y;\sigma) * I_h(x,y)$, with I_l and I_h respectively the low and resolution images and $G(x,y;\sigma)$ the smoothing filter, $\sigma_h^2 = \sigma_l^2 - \sigma^2$

$\Rightarrow$ Profile sharpness σ_l allows for reconstructing high resolution profile at edge points
$\Rightarrow$ New high resolution gradient field

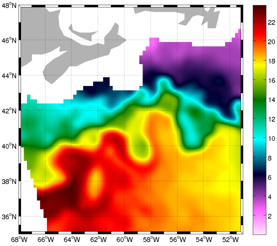
Enhanced resolution of SST fields

SST field reconstruction

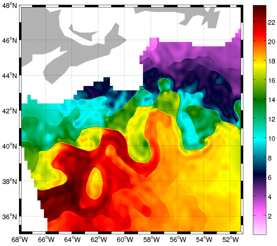
Minimization of the following objective function with contraints :

- on image
- on image gradient

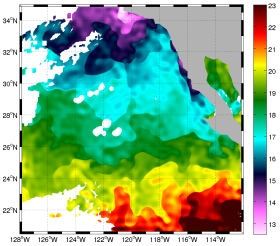
$$\int\int (I_h(x,y) * G(x,y,\sigma) - Il(x,y))^2 + \beta \left|\left|\nabla Ih(x,y) - \nabla\tilde{I}h(x,y)\right|\right|^2 dxdy$$



Gulf Stream : low resolution SST field



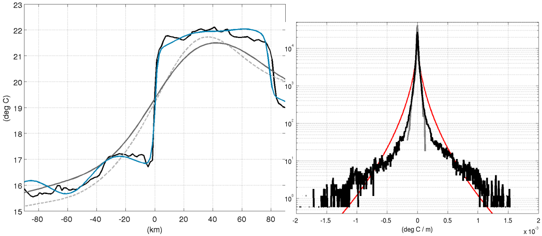
Gulf Stream : Reconstructed SST field



California : Reconstructed SST field

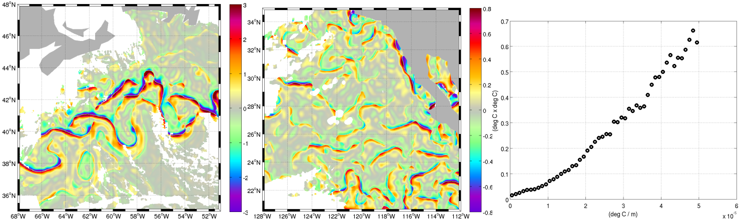
Enhanced resolution of SST fields

SST profile example



SST profiles from MODIS (black), AMSR-E (light gray), smoothed MODIS (gray) and reconstructed (blue) SSTs (left)
Normalized histogram of zonal SST gradient (right)

Anomalies



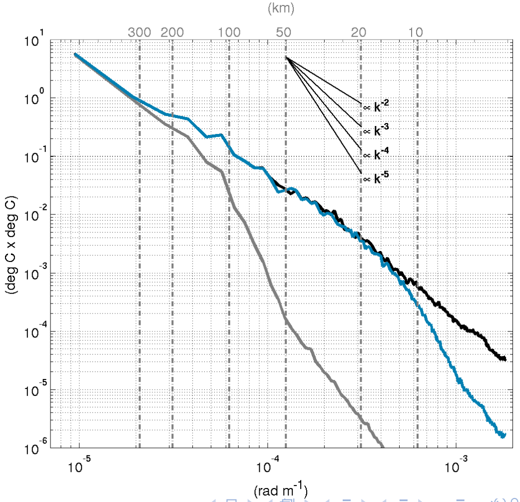
Reconstructed SST anomalies and anomaly versus low resolution gradient

Enhanced resolution of SST fields

Spectral analysis :

⇒ Reconstructed SST spectrum indistinguishable from that of the HR field at scales larger than 60 km and the energy levels are comparable up to ∼ 15 km

- missing energy : small structures not visible on low resolution images.



Outline

Conclusion

High resolution SST gradient and anomaly distribution

- non-Gaussian character highlighted
- gradient distributions fitted by the hyper-Laplacian distribution

High resolution phase

- relationship between high resolution anomalies and low resolution gradients
- enhanced resolution of the major fronts visible in the low resolution fields contribution
- profile model proposition (in practice, asymmetric model used)
- SST field reconstruction from SST gradient field
- link with the Lagrangian techniques, as proposed by *Desprès et la. (2011), Dencausse et al. (2014), Berti et al. (2014)* (not shown here)

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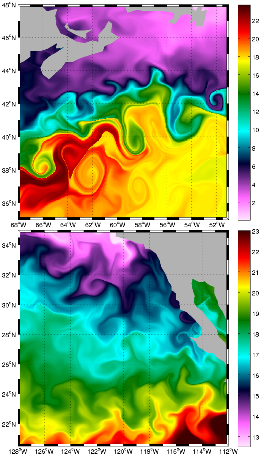

Lagrangian reconstructions