Statistical Emulation of High-Resolution SAR Wind Fields from Low-Resolution Model Predictions

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High-Resolution Data Application

- Describe and analyze the ocean dynamics in detail, particularly in coastal areas.
- Extend and improve numerical prediction models.
- Aid energy production, track oil spill disasters.
- Help the assessment of risks relevant to marine engineering, environment pollution.

Source: CLS (ex. Boost Technologies)
Motivation (1)

Satellite SAR (Synthetic Aperture Radar) Systems

😊 High spatial resolution, < 0.01°, ≈ 1 km
😊 Irregular sampling for a given region
😊 Low temporal resolution, every 7-to-10 days for temperate zones
Motivation (2)

**Numerical Model Predictions**

- 🎉 High temporal resolution, every 3 h or 6 h
- 🎉 Global coverage
- 🙁 Low spatial resolution, 0.5° for example

![Diagram of wind fields](image)
Motivation (3)

Use statistical emulation model

- to learn low-high resolution relationship

For new input LR data

- Derive HR (High Resolution) information from LR (Low Resolution) information
- Reconstruct HR wind fields for anywhere and at anytime
Problem Formulation

Regression Problem

- $y = f(x)$
- $x$ and $y$ are two-dimensional vector fields parameterized according to the zonal and meridional wind components
Problem Formulation

Regression Problem

\[ y = f(x) \]

\[ x \text{ and } y \] are two-dimensional vector fields parameterized according to the zonal and meridional wind components.

Learning Scheme

- Goal: learn regression function \( f \)
- From a training set \( \{(x_k, y_k)\}, \ k \in (1, n) \)
- Find an optimal \( f^* \): minimize the regression errors
  \[ \sum_{k=1}^{n} (y_k - f^*(x_k)) \text{ or } \sum_{k=1}^{n} (y_k - f^*(x_k))^2 \]
Data Set and Study area

**Data set**
- Select the closest ECMWF data to SAR data acquisition; very different pairs are rejected
- 758 pairs for the period 2005–2010

**Study Area**
- Southwestern coastal sea of Bergen, Norway
- Many islands, mountains, and fjords in coastal area
**Data Set and Study area**

### Data set
- Select the closest ECMWF data to SAR data acquisition; very different pairs are rejected
- 758 pairs for the period 2005–2010

### Study Area
- Southwestern coastal sea of Bergen, Norway
- Many islands, mountains, and fjords in coastal area ⇒ Remarkable local effects: coastal jets, wind shadows, land-sea breezes...
Data Set Examples (1)
Data Set Examples (2)
Physical Constraint Analyses (1)

Global Analyses

Mean of the difference between ECMWF and SAR

Standard deviation of the difference ECMWF-SAR
Physical Constraint Analyses (2)

Transect perpendicular to the coast

Transect line

ECMWF and SAR mean

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Physical Constraint Analyses (3)

Scatterplots of ECMWF-SAR for: offshore, coast, fjord feature grid point

Offshore feature point 9
(N62.25°, E3.78°)

Coastal feature point 8
(N62.07°, E5.22°)

Fjord feature point 1
(N61.15°, E5.95°)

Non-linear LR-HR relationship in coastal and fjord area, compared to offshore area
Proposed Regression Model

- Point-specific model: a transfer function for each HR grid point
- Regression approach choice
- Regression variables (predictors) definition

\[ \text{Model } f_{p,q} : x \rightarrow y \]

\( \{x_i\} \)

\( \{y_i\} \)

HR grid

LR grid

Regression variables definition

Regression Approach

\[ (p,q) \]
Regression Technique Choices

- Analog methods – standardized responses of similar cases:
  \[ f(x) = \sum_{s=1}^{n} w_s g(x, x_s) \]  
  \[ f(x) = \sum_{s=1}^{n} w_s g(x, x_s) \]  

- Multiple Linear Regression (MLR) – linear relation between inputs and outputs:
  \[ f(x) = \omega^t x + b \]  

- Non-Linear SVR (Support Vector Regression) – optimal non-linear kernel-based model, linear regression model in a space defined by a non-linear function mapping:
  \[ f(x) = \omega^t \Phi(x) + b \]
Global information: the first $m$ Principle Components (PCs) in the Empirical Orthogonal Functions (EOFs) space

Local information: exploits the LR wind information within a local neighborhood

What is the best box size?
Entropy-based information selection step:

- Conditional entropy $H(y|\mathbf{x})$ is a measure of amount of uncertainty remaining about $y$ after $\mathbf{x}$ is known.
- For a given HR grid point $p$, we select the LR grid points with the lowest conditional entropy values for HR field at this point:

$$H(y_p|\mathbf{x}_q) = -\sum_{j=1}^{m} \sum_{i=1}^{n} P(y_p = y_j, \mathbf{x}_q = \mathbf{x}_i) \log P(y_p = y_j|\mathbf{x}_q = \mathbf{x}_i)$$  \hspace{1cm} (4)
Evaluation

• Qualitative and quantitative evaluation
• Cross validation
  • 95% randomly sampled for training
  • 5% for reconstruction

\[ \{x_i, y_i\} \quad \ldots \quad \ldots \quad \{x_j, y_j\} \quad \ldots \quad \{x_k, y_k\} \]

\[ f : x \rightarrow y \quad \Rightarrow \quad y'_j = f(x_j) \]

• Regression performance for 12 HR grid points
Regression Variable Influence

Information type: global, local and entropy-based information

**Nearest Neighbor**

**K-Nearest Neighbor**

**MLR**

**SVR**

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Regression Approach Influence

Compared approaches: Nearest Neighbor (NN), Weighted Average Analog (AN), Multiple Linear Regression (MLR), Support Vector Regression (SVR)
Optimal Regression Model

- SVR
- Local or non-local entropy-based variables’ selection
Statistical Properties (1)

Global Analyses

Mean of the difference between ECMWF and SAR data

Mean of the difference between Reconstruction and SAR data
Statistical Properties (2)

Transect perpendicular to the coast

Transect line

ECMWF, SAR and Reconstruction speed mean
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Statistical Properties (3)

Scatterplots of SAR-ECMWF and of SAR-Reconstruction for:
- offshore, coast, fjord feature grid point

Offshore feature point 9
(N62.25°, E3.78°)

Coastal feature point 8
(N62.07°, E5.22°)

Fjord feature point 3
(N61.91°, E5.80°)
Reconstruction Example (1)
Reconstruction Example (2)
Reconstruction Example (3)
Thanks!