Extreme Surface and Near-Bottom Current Speeds in the northwest Atlantic

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POMSS
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Introduction

- The **prediction of extreme ocean currents** is of interest from both a purely scientific point of view as well as for practical applications.
- **Scientific**: What roles do the mean flow or atmospheric forcing conditions play in driving extreme surface currents? What is the vertical structure of extreme currents?
- **Practical**: when designing and insuring offshore oil platforms or subsurface pipelines it is important to have estimates of what extreme conditions might be experienced by these devices
- **Aim**:

Use predictions of tidal and non–tidal currents to describe and map extreme currents in the northwest Atlantic

- **Outline**:

1. Data sources
2. Background flow
3. Predicting and mapping extreme currents
4. The importance of tides
5. Physical interpretations
6. Conclusions and future work

- **Data**:

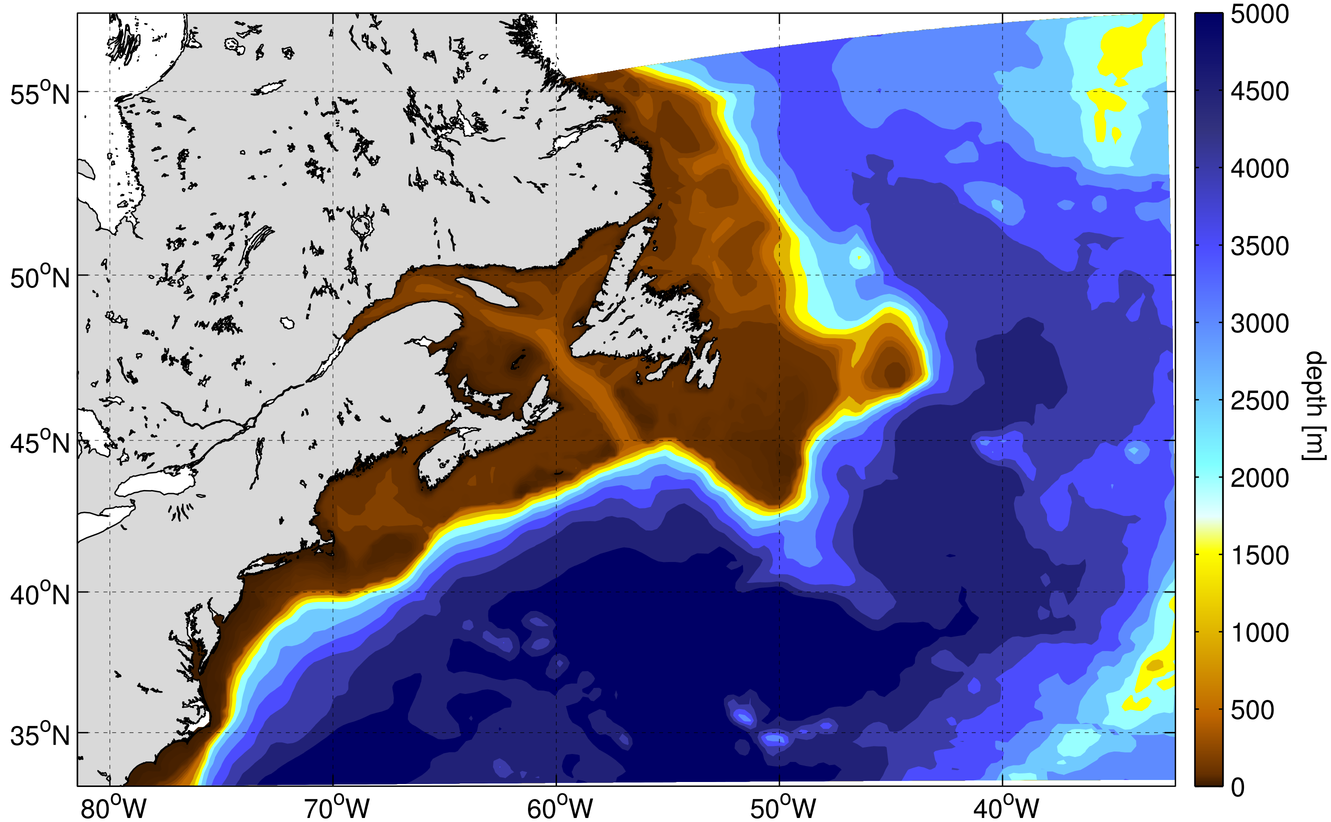
- **Non–tidal currents**: 17–year hindcast (1988–2004) of the ocean state using a general circulation model

- **Tidal currents**: Predictions of tidal currents at all model grid points using WebTide and 8 tidal constituents (ack. Kyoko Ohashi)

- **Sea level**: Long hourly records of sea level at Halifax (91 years) and Wakkanai, Japan (44 years) used to demonstrate the extemal analysis techniques

Hindcast Model

- 3D general circulation model: **NEMO v2.3**
- **1/4 degree** horizontal resolution, **46 *z*-levels** with thicknesses increasing from 6 m at the surface to 250 m at the bottom
- Bathymetry derived from **ETOPO2** *[Smith and Sandwell, 2007]*



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- Bathymetry derived from **ETOPO2** *[Smith and Sandwell, 2007]*
- Forced by 6–hourly **wind**, **temperature**, and **humidity** (10 m), 12–hourly longwave and shortwave **radiation**, and monthly **precipitation** at a resolution of **2 degrees** *[Large and Yeager, 2004]*
- **Lateral BCs**: (i) free slip at coast, (i) adaptive open boundary condition elsewhere (e.g., *Sheng and Tang, 2003*)
- **Spectral nudging** to climatological seasonal cycle (annual and semi–annual)
- Smoothed **semi–prognostic method** to correct for differences between observed and modeled density fields.

Fisheries and Oceans Canada | Pêches et Océans Canada | Canada

FISHERIES AND OCEANS CANADA
Ocean and Ecosystem Science (OES)

WebTide Global Data (v0.65)

File Control Navigate Layers WebTide Help

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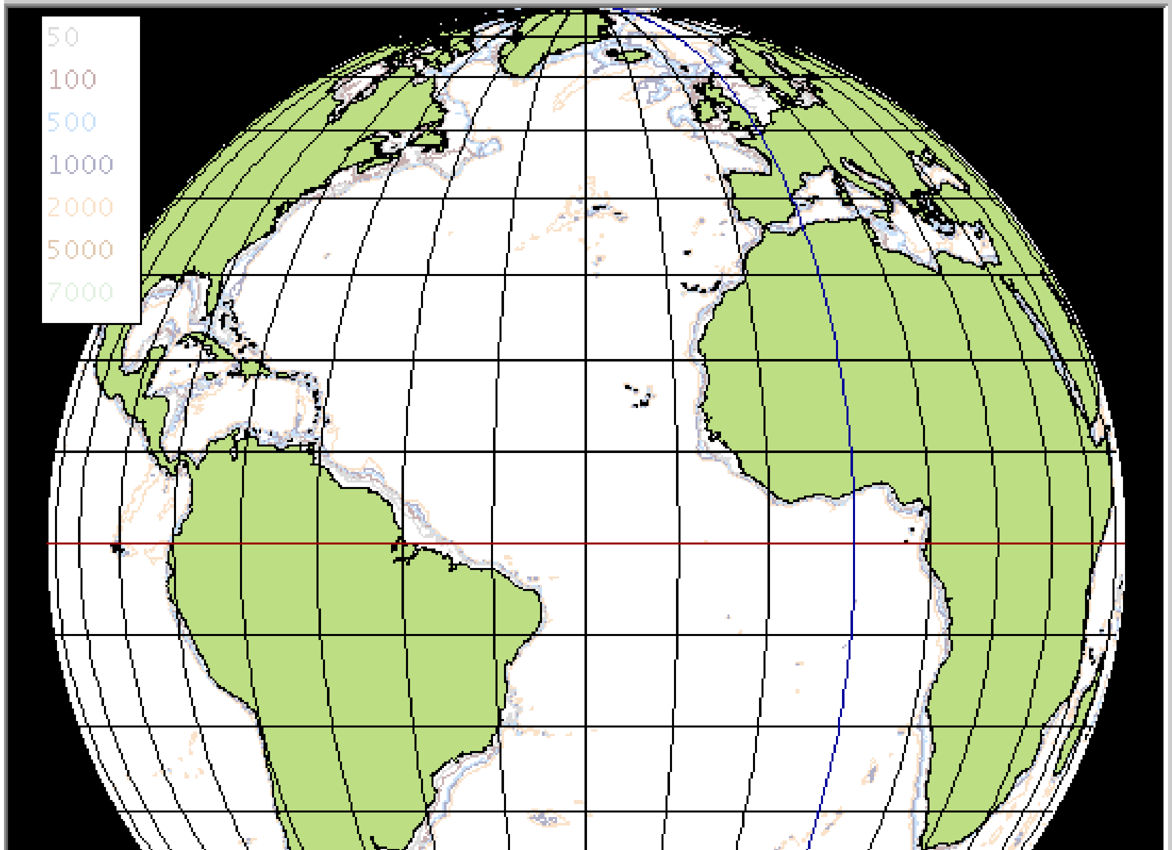
Ocean Science Division
Bedford Institute of Oceanography
Fisheries and Oceans Canada



WebTide Commands
- Add Tide Marker
- Delete Tide Marker
- Tide Marker Parameters
- Edit Parameters
- Run_Elevation_Prediction
- Display Elevation Graphs
- Get Elevation Prediction
- Clear Elevation Prediction
- Run_Current_Prediction
- Display Current Graphs
- Get Current Prediction
- Clear Current Prediction
- Cancel

Tidal Predictions

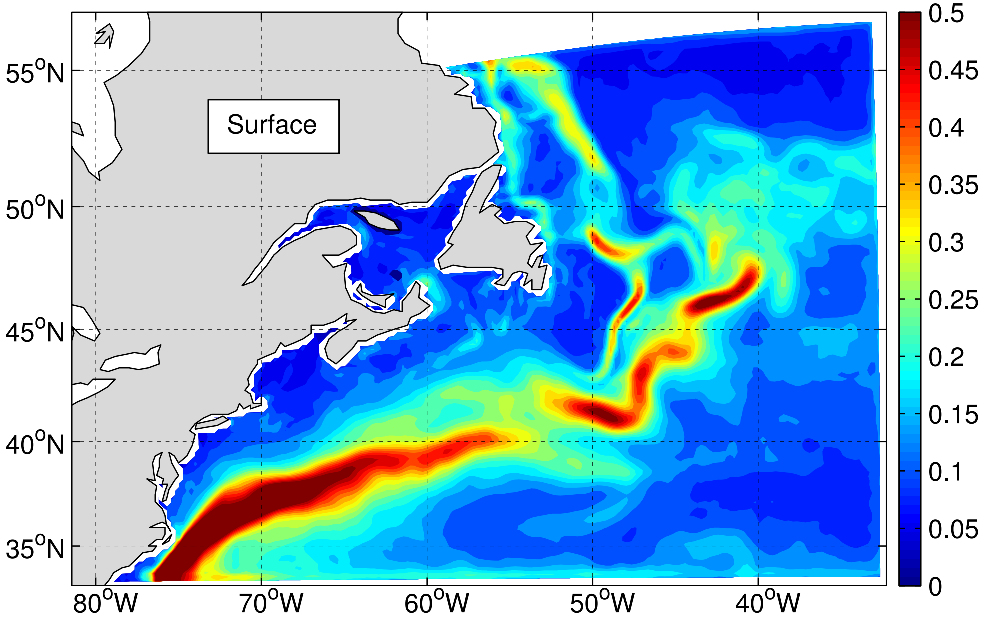
- Tidal constituent *i* oscillations **sinusoidally** with frequency ω_i , amplitude A_i and phase ϕ_i
- WebTide code provides **predictions** of A_i and ϕ_i
- Tidal currents are **reconstructed** from:

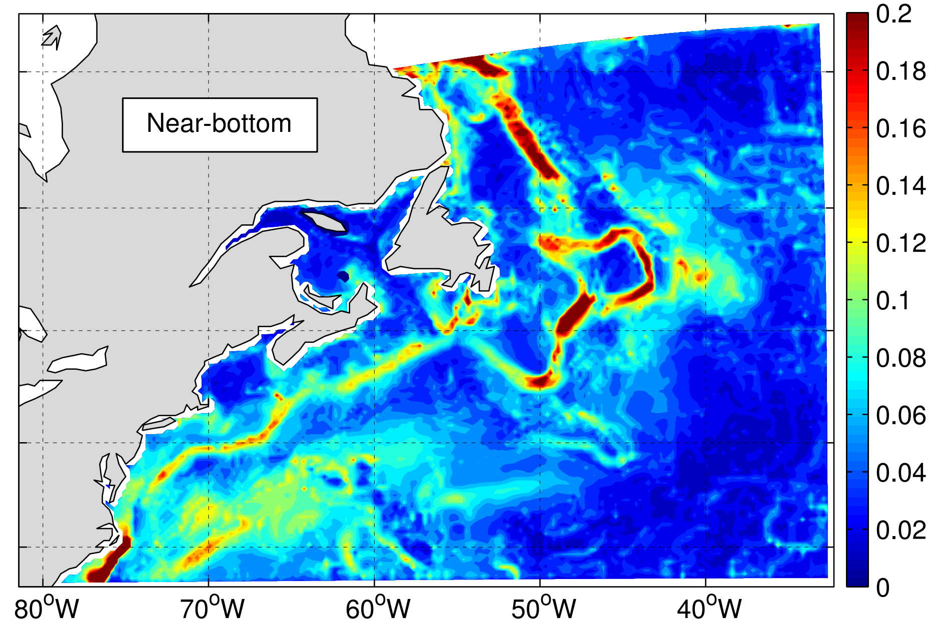
$$
\begin{aligned}
u_t^{\mathrm{T}} &= \sum_i A_i^{(u)} \cos(\omega_i t + \phi_i^{(u)}) \\
v_t^{\mathrm{T}} &= \sum_i A_i^{(v)} \cos(\omega_i t + \phi_i^{(v)})
\end{aligned}
$$

sum over tidal constituents:
M2, K1, N2, S2, O1, M3, M4, and M6

Background State

- The background state is defined as the **time-mean** of the hindcast current speeds
- Dominated by the **Gulf Stream**, the **North Atlantic Current** and the **Labrador Current**, and flow along the **shelf break**
- **Seasonality**: currents are generally stronger in fall/winter (SONDJF) than in spring/summer (MAMJJA)

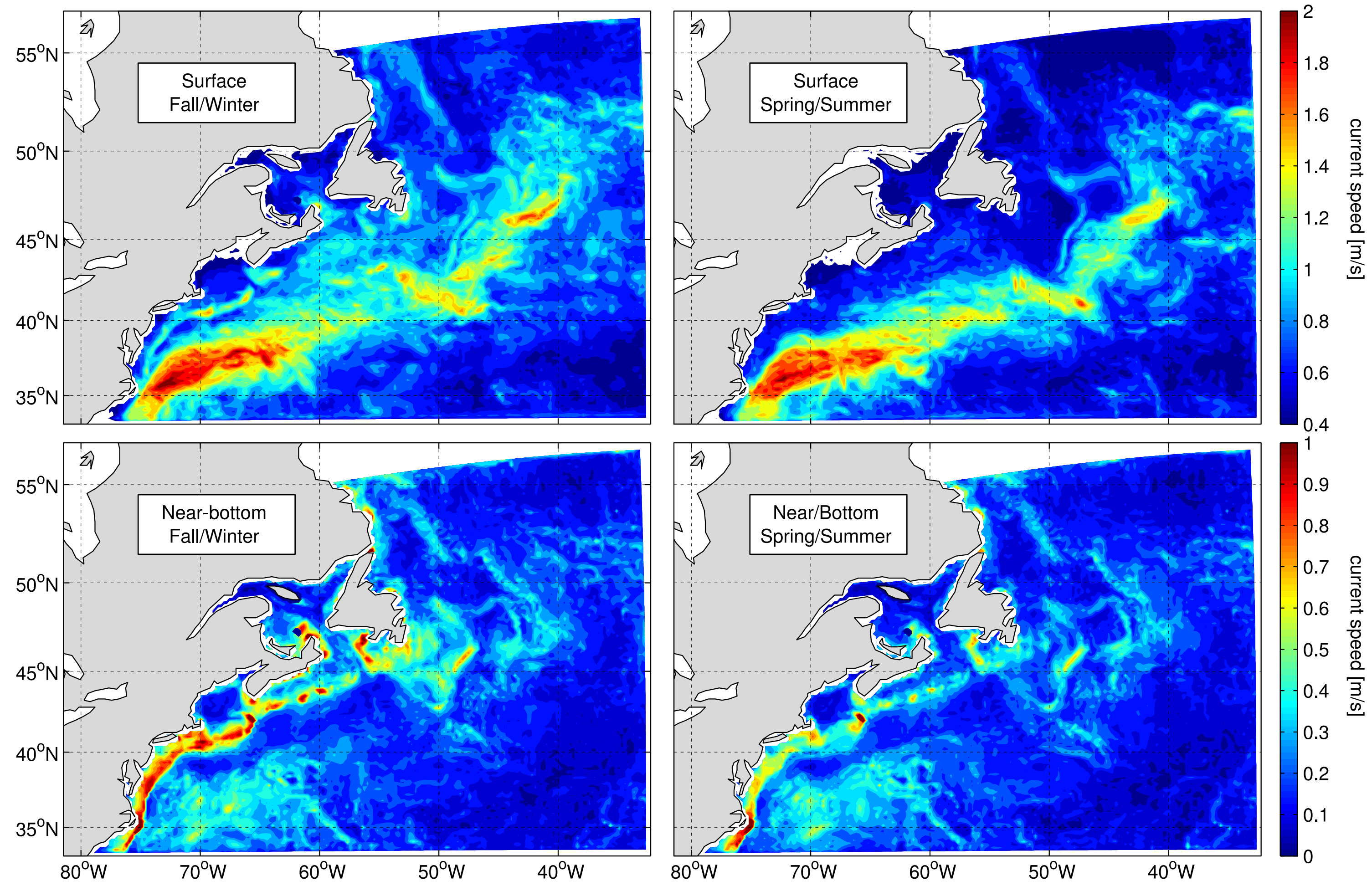




near–bottom = lowest model z–level

Simulated Maximum Currents

- **Maximum** of 17-year hindcast current speeds
- Background flow, flow over shallow regions, shelf break...



Extremal Analysis

- Can calculate maximum over 17 years.... but what about longer return periods? **Extremal analysis!**
- Consider a sequence of *N* iid random variables $\{\eta_t | t = 1, 2, \ldots, N\}$
- Let M_n denote the maximum of the first *n* in the sequence:

$$M_n = \max(\eta_1, \eta_2, \ldots, \eta_n)$$

- As $n \to \infty$ the probability that M_n is less than or equal to *x* converges to one of three distribution types: Gumbel (Type I), Frechet (Type II), or Weibull (Type III)
- These distributions are conveniently summarized by the GEV dist. :

$$P_{\mathrm{GEV}}(x \geq M_n) = \exp\left\{ - \left[1 + \xi \left(\frac{x - a}{b} \right) \right]^{-\frac{1}{\xi}} \right\}$$

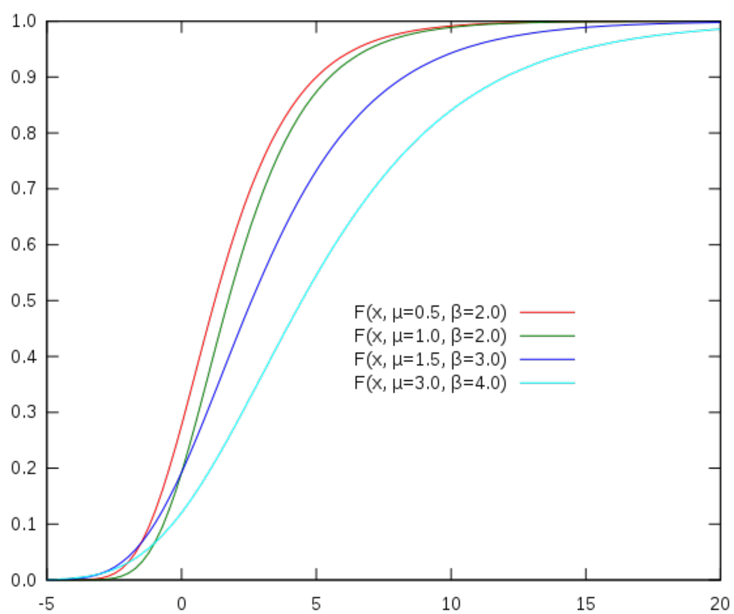
The Gumbel Distribution

- The GEV distribution

$$P_{\mathrm{GEV}}(x \geq M_n) = \exp\left\{-\left[1+\xi\left(\frac{x-a}{b}\right)\right]^{-\frac{1}{\xi}}\right\}$$

reduces to the Type I (or Gumbel) distribution as $\xi \rightarrow 0$

$$P_{\mathrm{I}}(x \geq M_n) = \exp\left[-\exp\left(-\frac{x-a}{b}\right)\right]$$

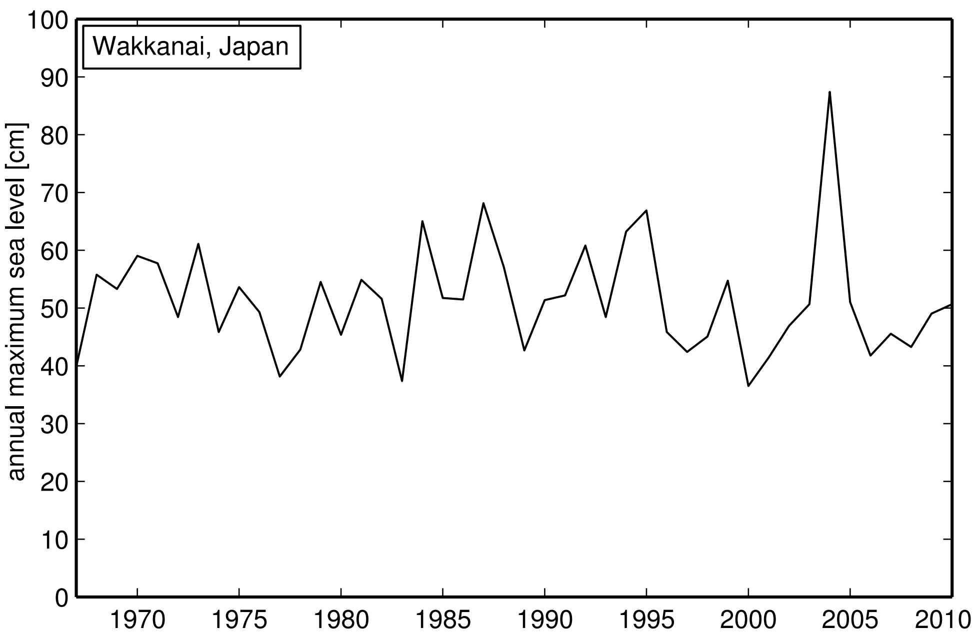


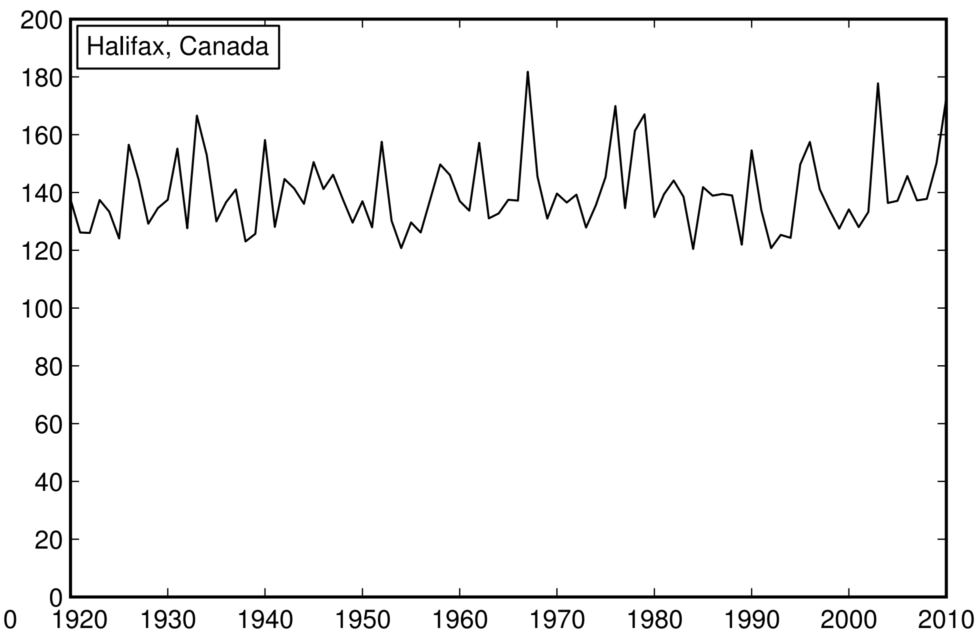
This distribution has often been used to model extreme values (e.g., sea level)

It lends itself well to predicting long return–period extreme events

Example: Extreme Sea Level

- Use sea level from **Halifax** and **Wakkanai** to illustrate the extremal analysis method (i.e., fitting the Gumbel distribution)
- Why did I choose these stations?
  - **Long** (>40yrs): useful to test predictions of long return-period extremes
  - Halifax is **tidally dominant** while Wakkanai is **tidally weak**
- Consider the **annual maximum** sea level:





Example: Extreme Sea Level

- Fit the **GEV distribution** to these annual maxima using **maximum likelihood** and get estimates of the GEV parameters $\left(a, b \text{ and } \xi\right)$.
- ξ is not statistically different from **zero** (5% significance level) so fit the **Gumbel distribution** instead and get estimates of a and b.

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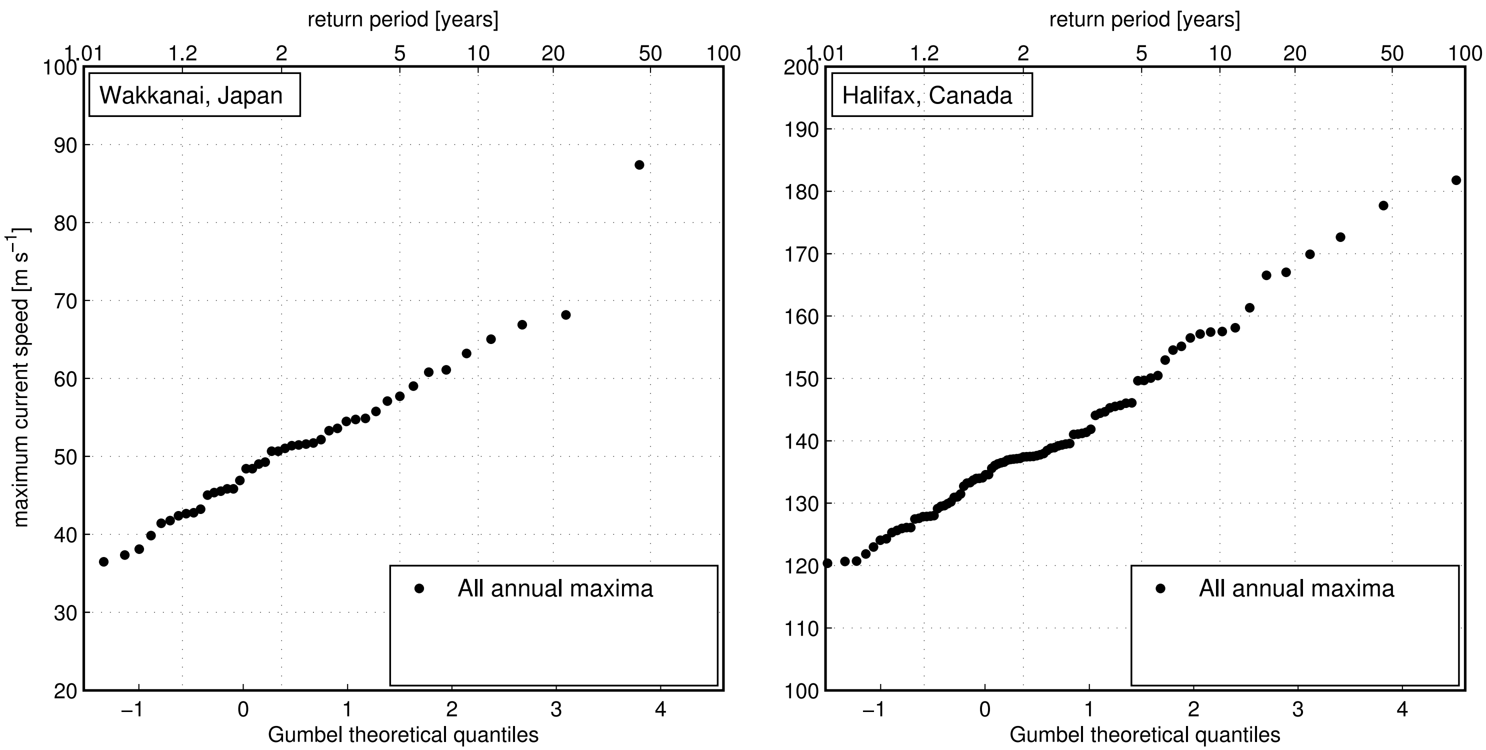

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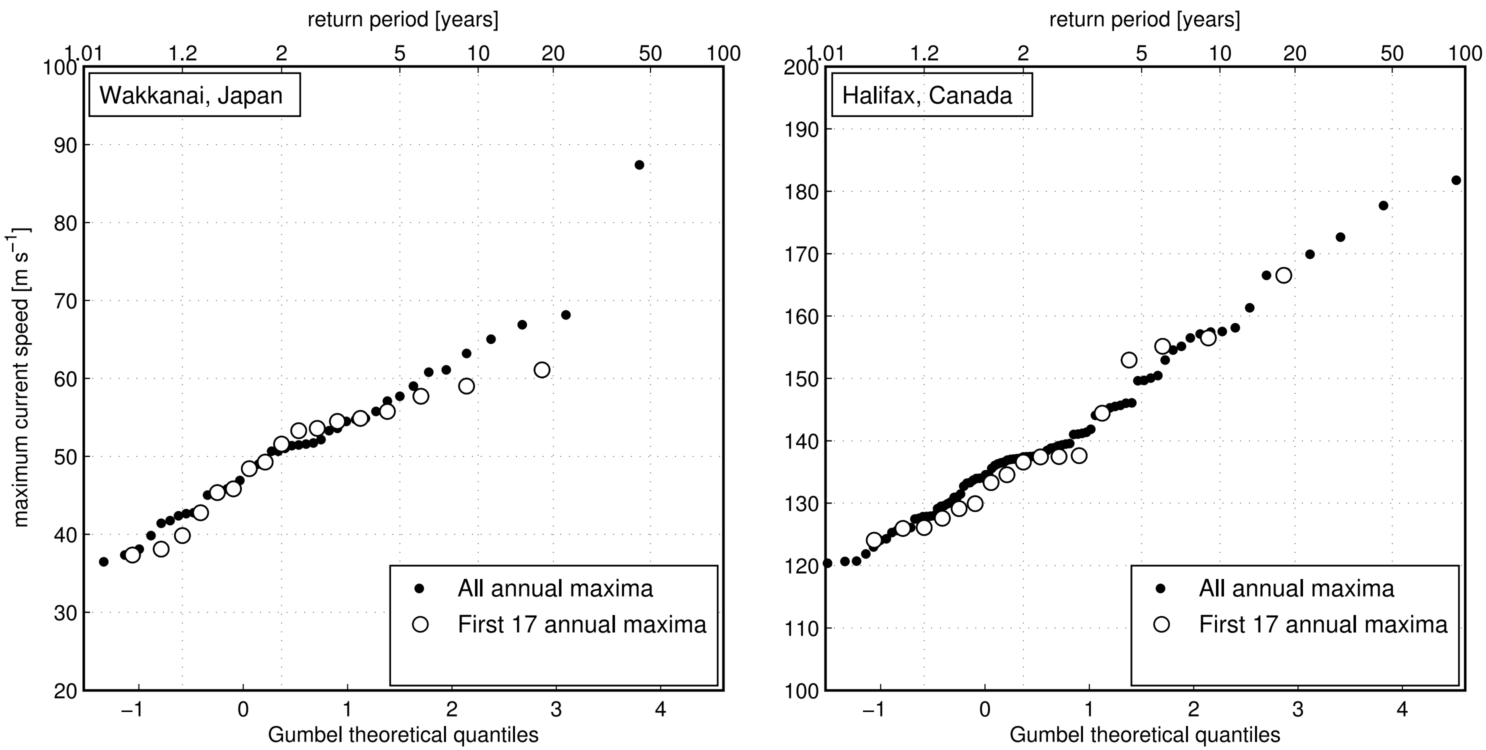

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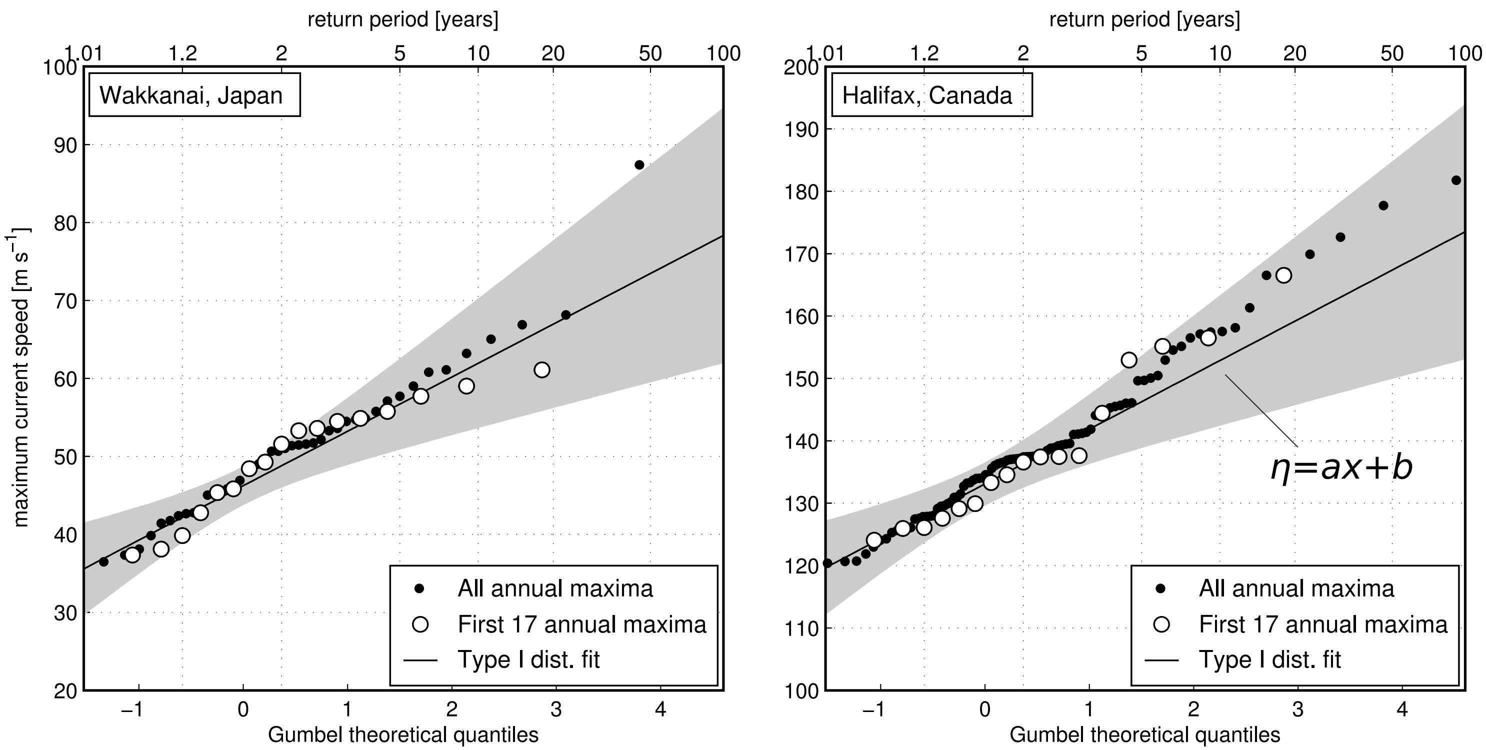
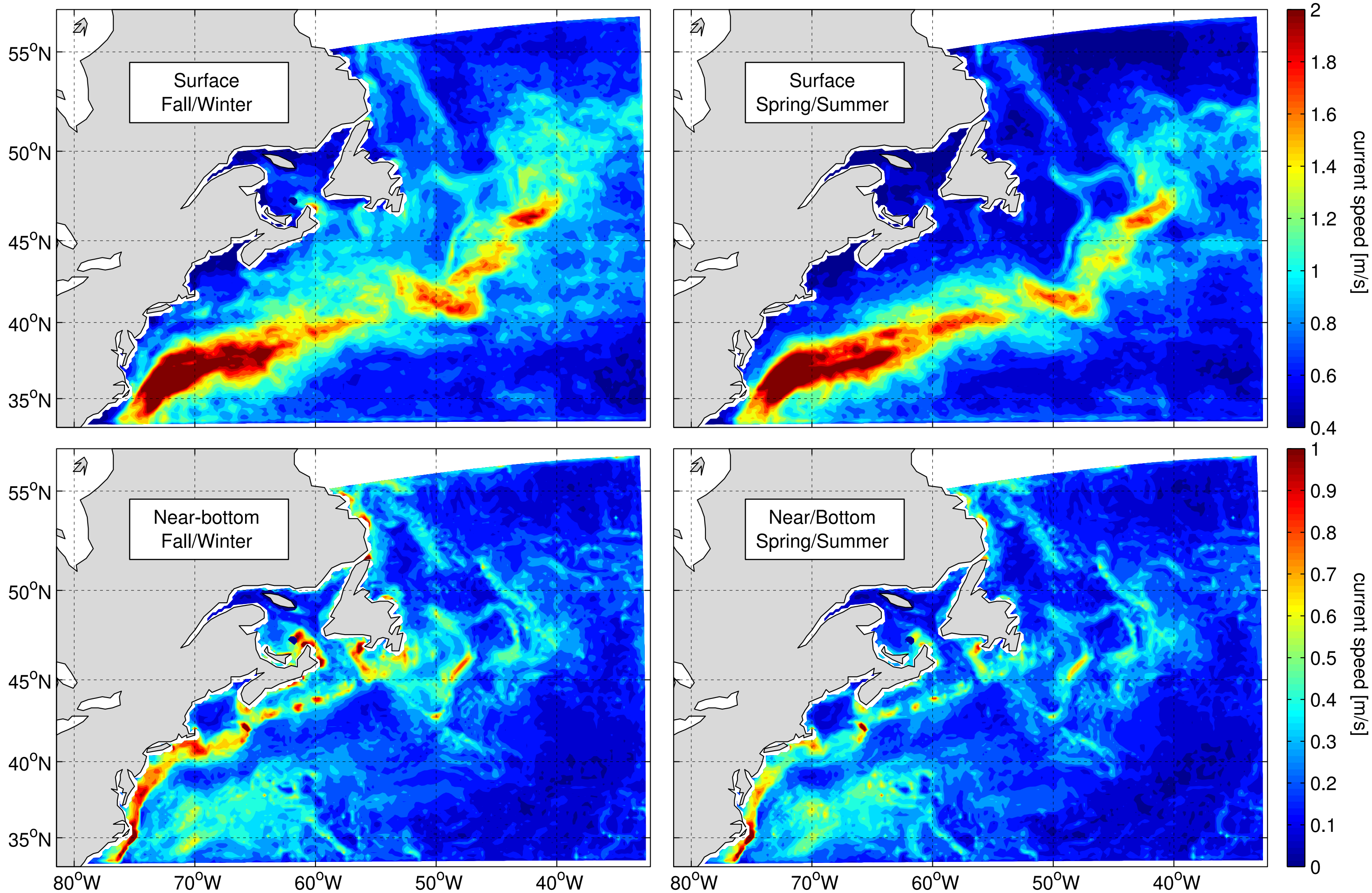


50-Year Extreme Currents

- Use this method to predict the **50-year extreme** current speeds at each location from 17 annual maxima:



The Importance of Tides

- We have ignored the influence of **tidal currents** which can be large, and even **dominant**, in some parts of the **northwest Atlantic**.

- Write current velocity (u, v) as a sum of **tidal and non-tidal components**:

$$(u_t, v_t) = (u_t^{\mathrm{NT}} + u_t^{\mathrm{T}}, v_t^{\mathrm{NT}} + v_t^{\mathrm{T}})$$

- To quantify the importance of tides at each location, take the ratio of the **total standard deviation** of tidal currents to the total standard deviation of non-tidal currents:

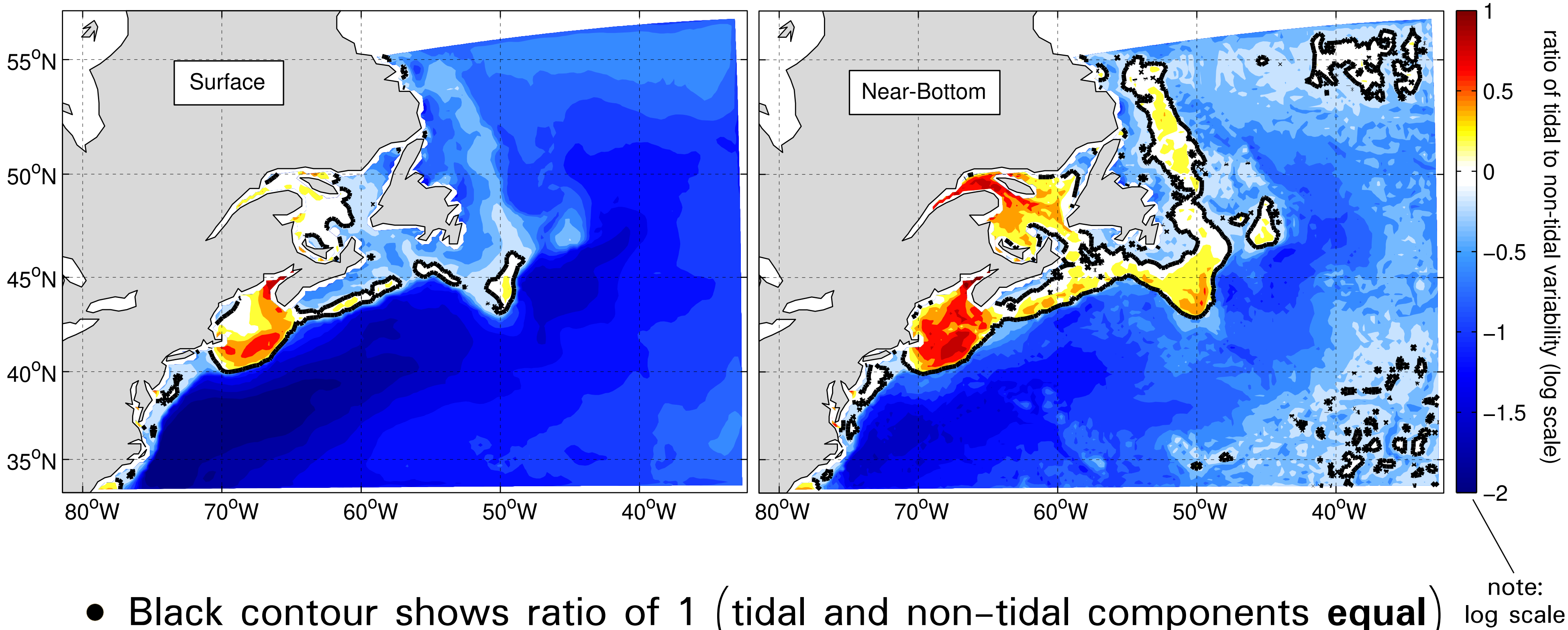
$$\frac{\sigma^{\mathrm{T}}}{\sigma^{\mathrm{NT}}} = \frac{\sqrt{(\sigma_u^{\mathrm{T}})^2 + (\sigma_v^{\mathrm{T}})^2}}{\sqrt{(\sigma_u^{\mathrm{NT}})^2 + (\sigma_v^{\mathrm{NT}})^2}}$$

>>1 tidally dominant

<<1 tidally weak

The Importance of Tides

- $\frac{\sigma^{\mathrm{T}}}{\sigma^{\mathrm{NT}}}$ **mapped** at each location in the northwest Atlantic



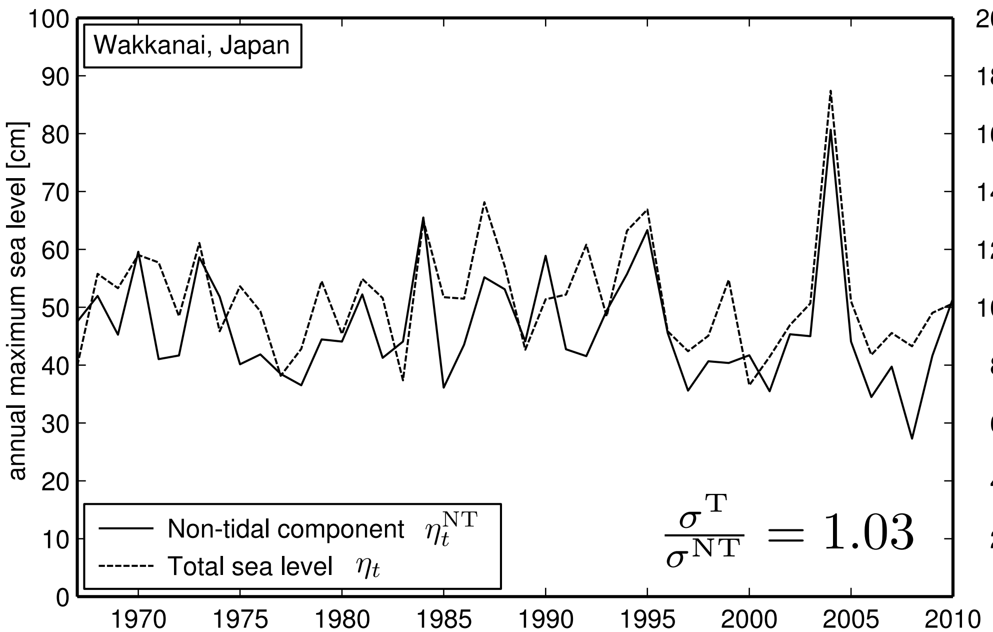
- Black contour shows ratio of 1 (tidal and non–tidal components **equal**)
- Tides are **dominant** in shallow regions, especially near the bottom.

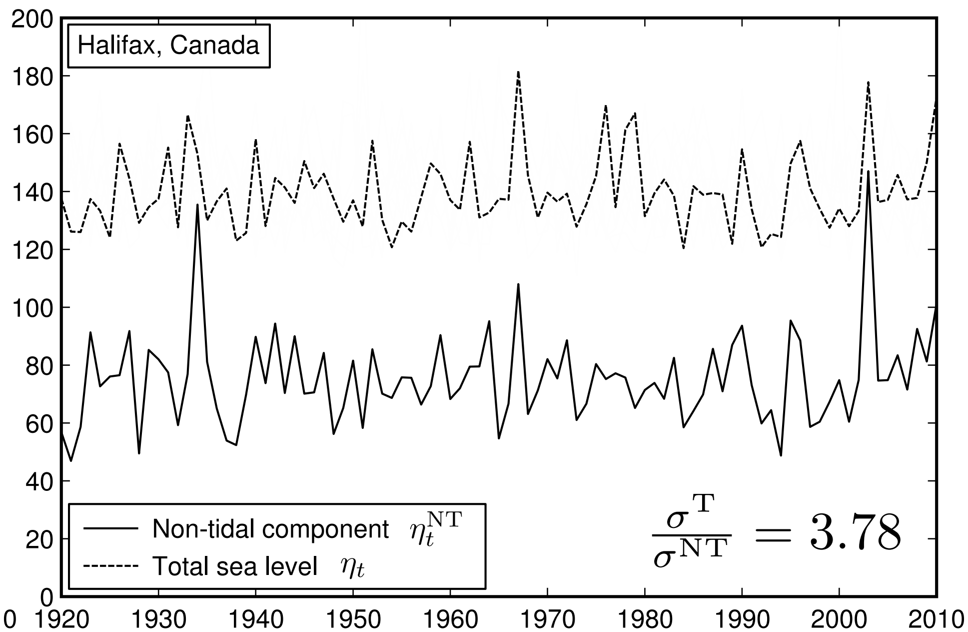
Example: Extreme Sea Level

- Consider sea level at Halifax and Wakkanai and write:

$$\underbrace{\eta_t}_{\text{tide gauge}} = \underbrace{\eta_t^{\mathrm{NT}}}_{\text{residual}} + \underbrace{\eta_t^{\mathrm{T}}}_{\text{predicted from T\_TIDE}}$$

- Annual maximum of η_t^{NT} and η_t :





Example: Extreme Sea Level

- The joint probabilities method (JPM) includes the **effect of tides** to extract reliable return–periods for extreme sea levels over **long periods**
- Assumes tidal and non–tidal components are independent and convolves the probability distributions to obtain the **joint probability distribution**
- Here we take an equivalent **Monte Carlo** approach
- The non–tidal component is **repeated** *M* times and each time adding a tidal component with **randomized phase**:

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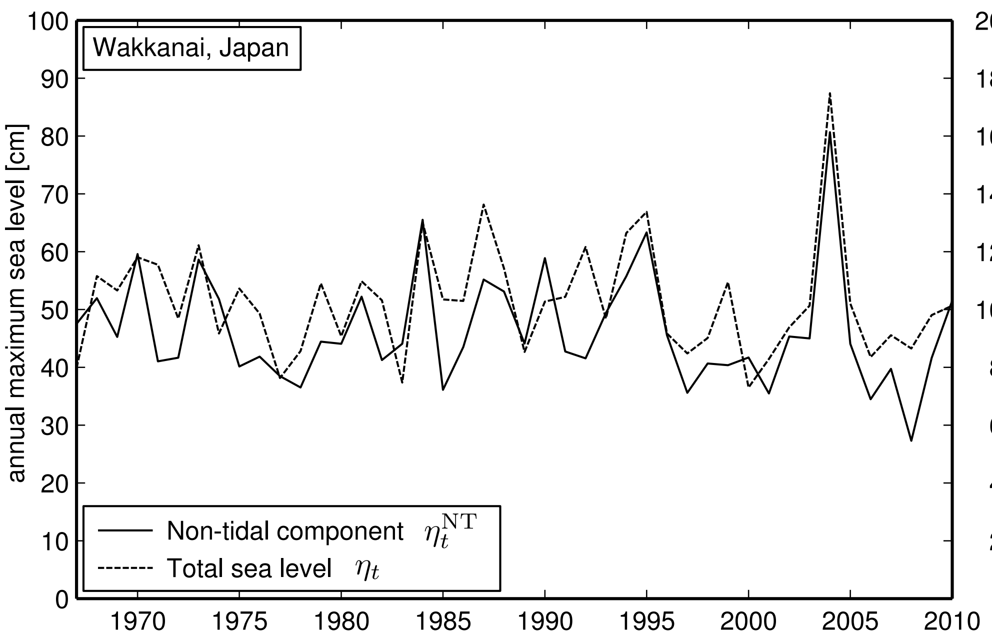
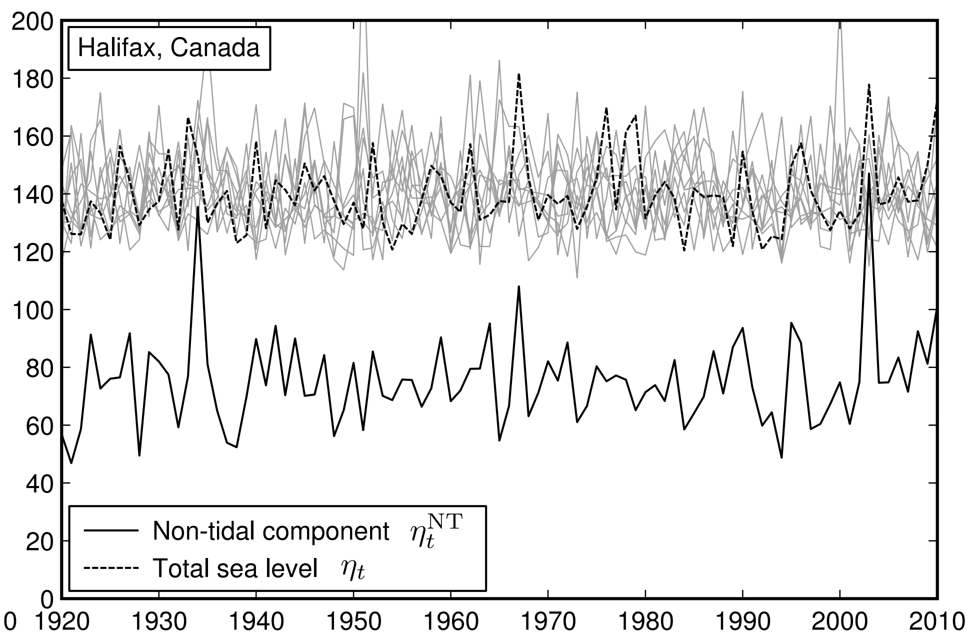
$M = 10$





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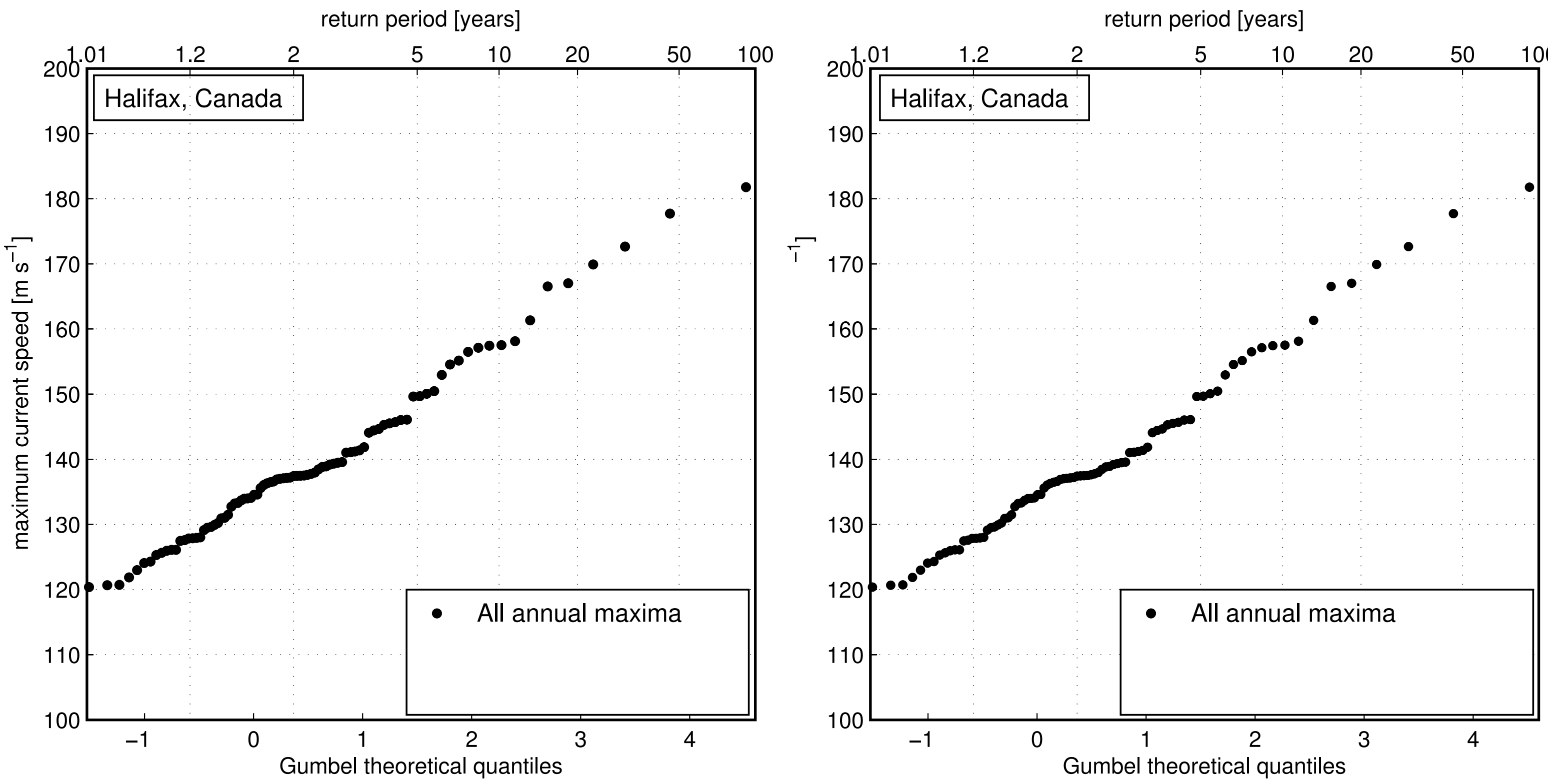

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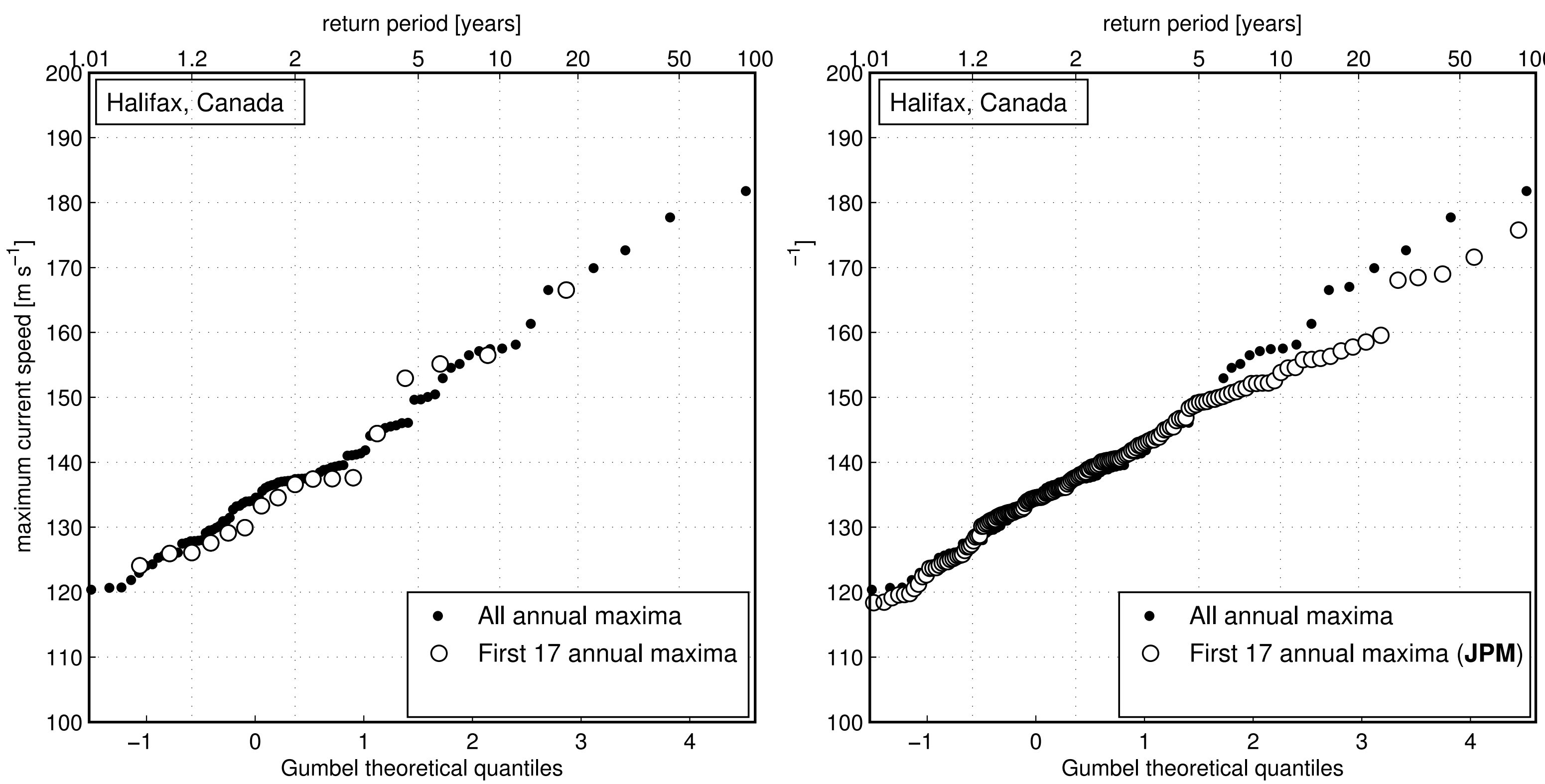

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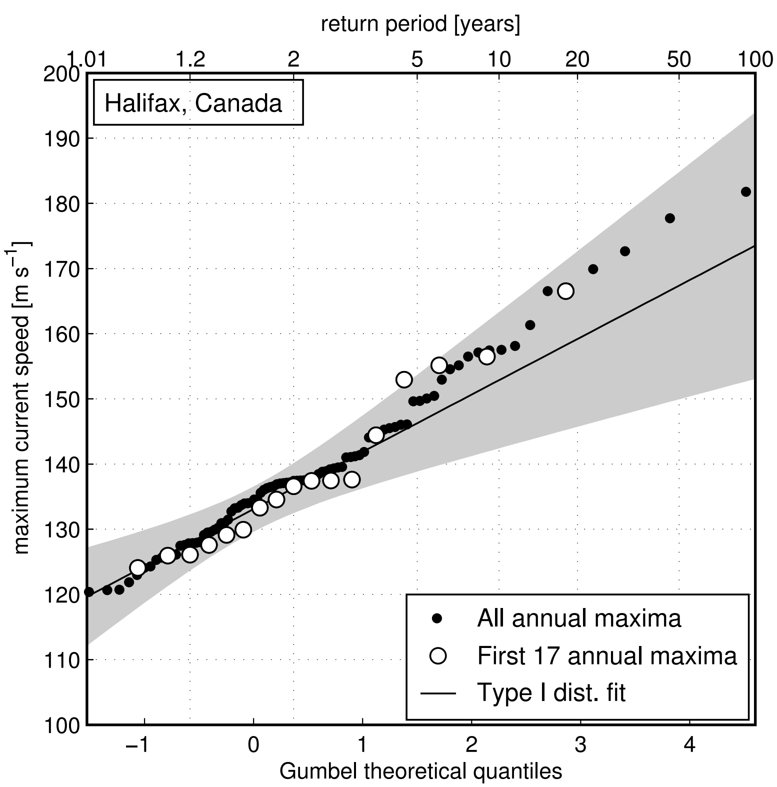

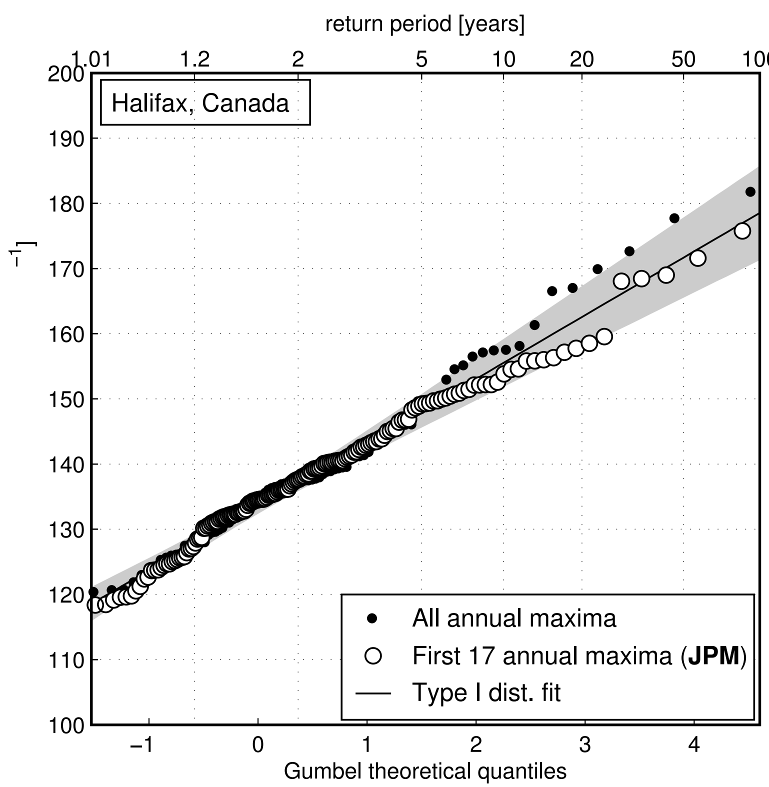

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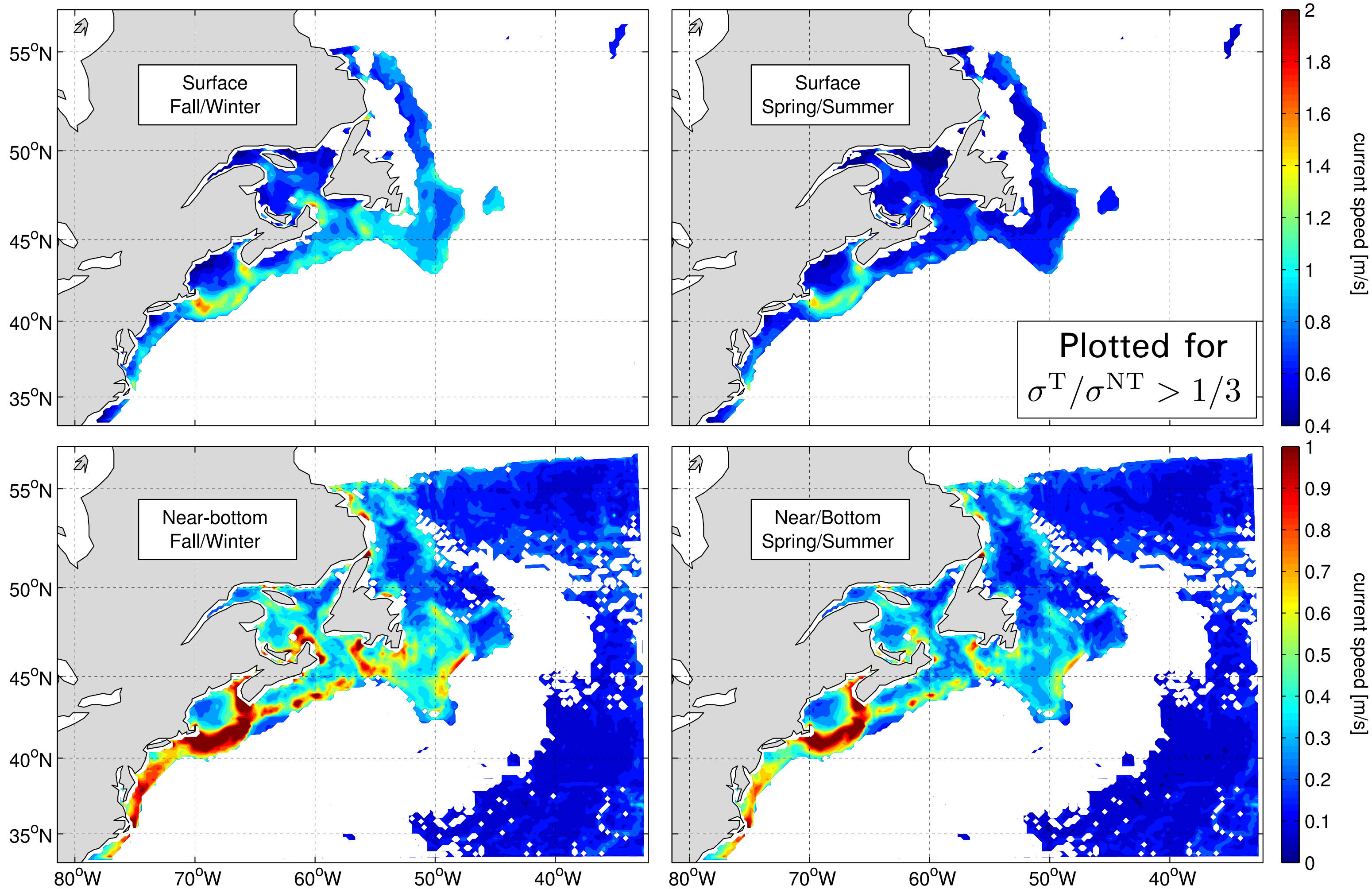
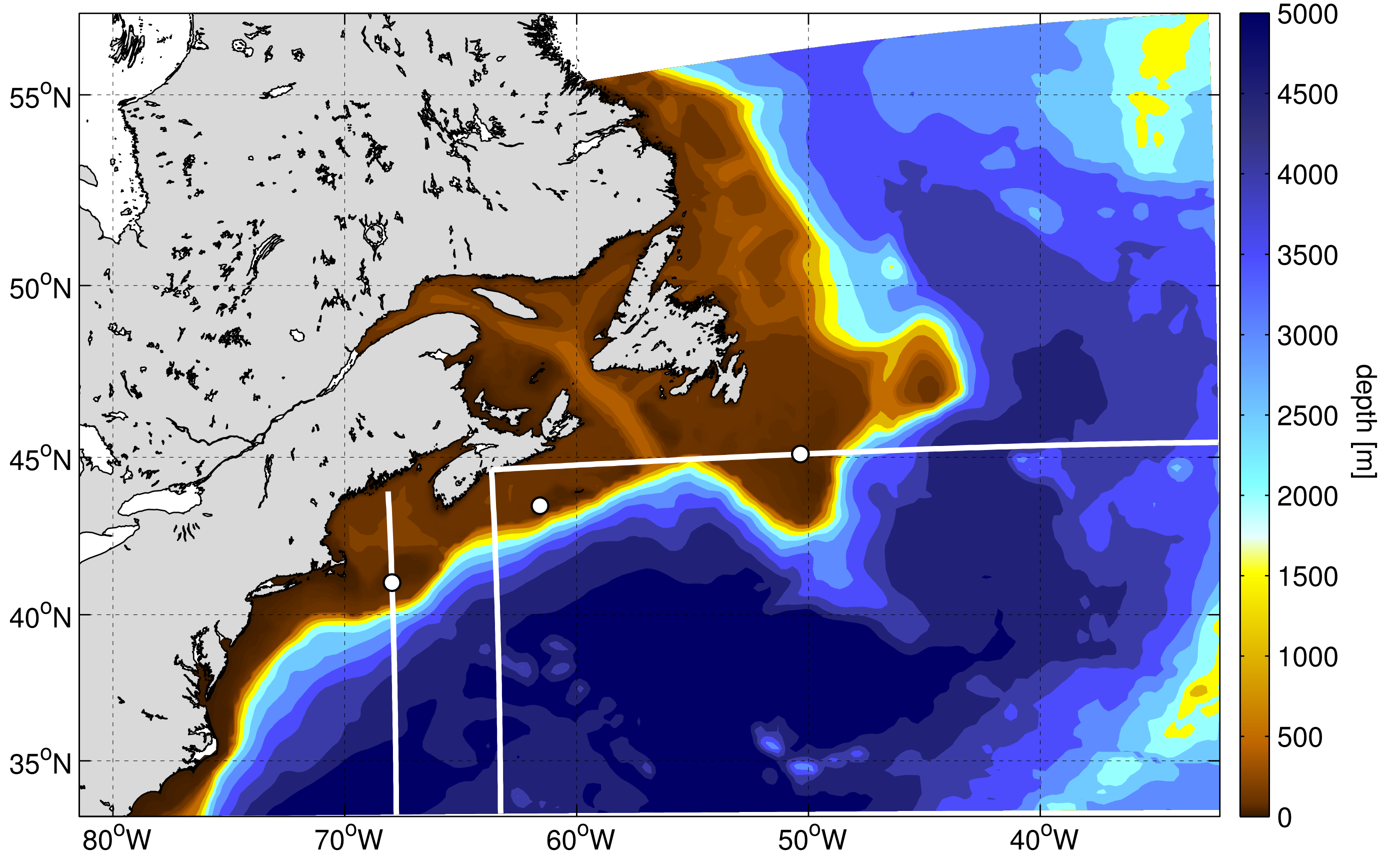
50-Year Extreme Currents

- 50–year **extreme current speeds** at each location from 17 annual maxima and predictions of tidal currents (**Monte Carlo JPM**):



Selected Locations and Transects

- 50–year extreme current speeds have been calculated **along** several **sections** (lines) and **depth profiles** (open circles):



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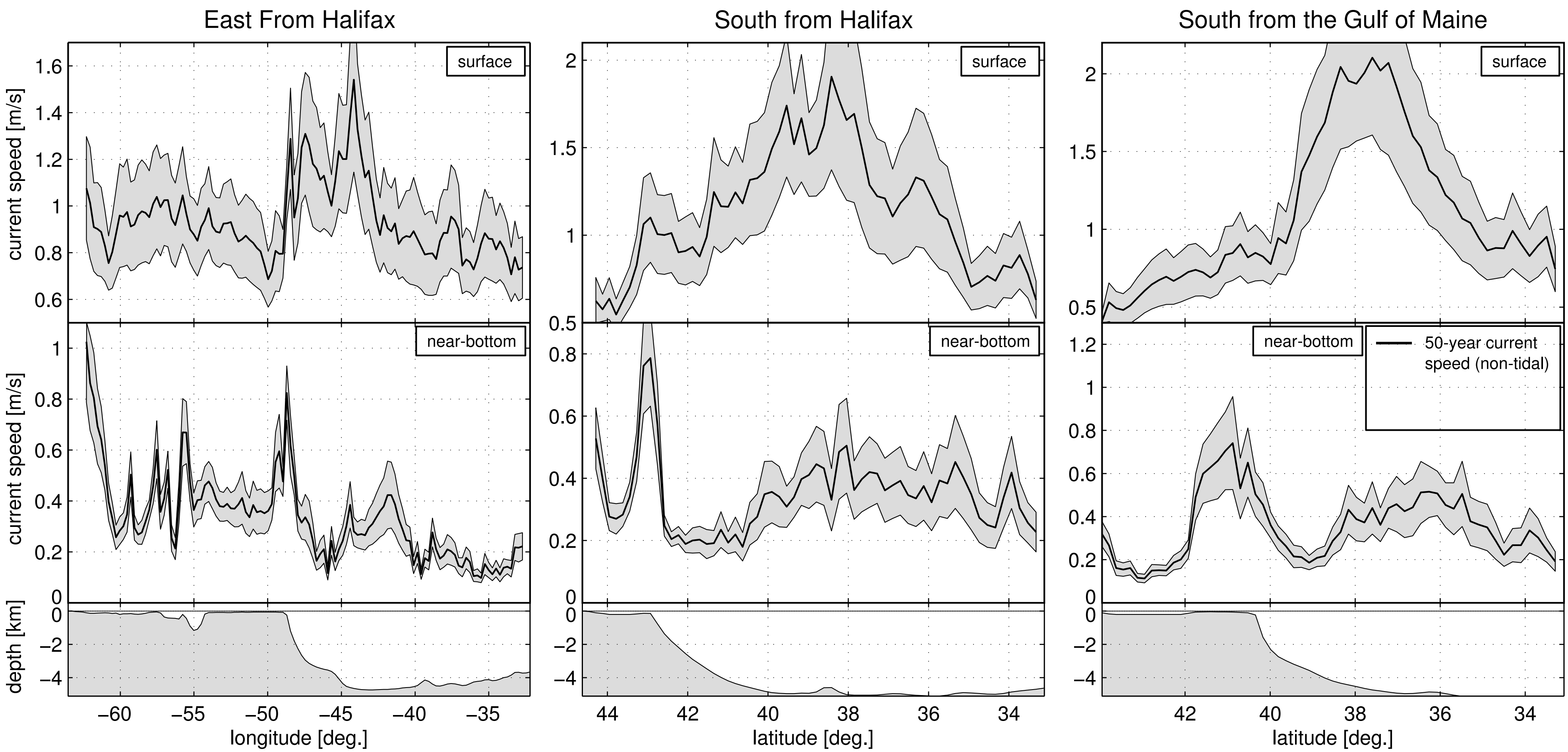

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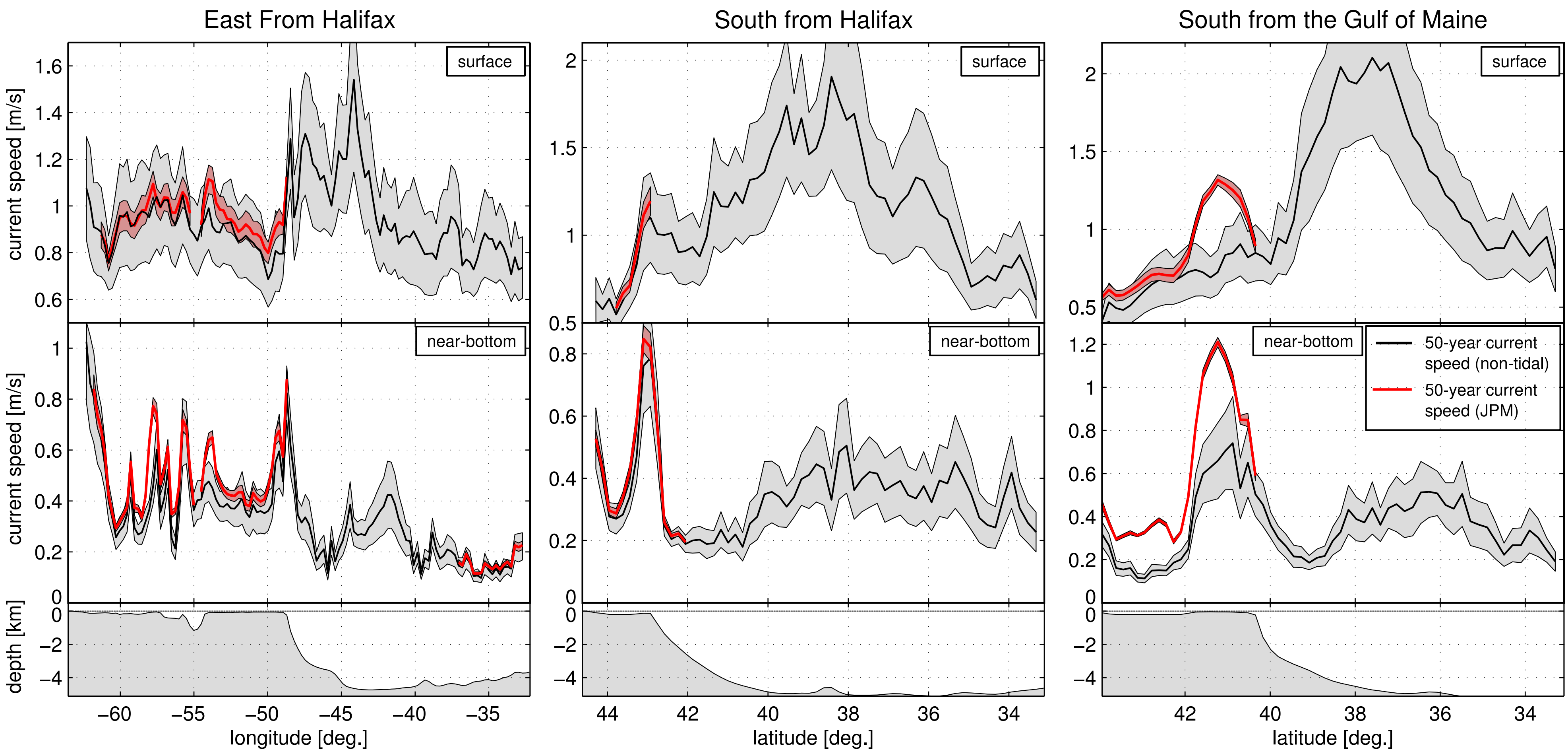

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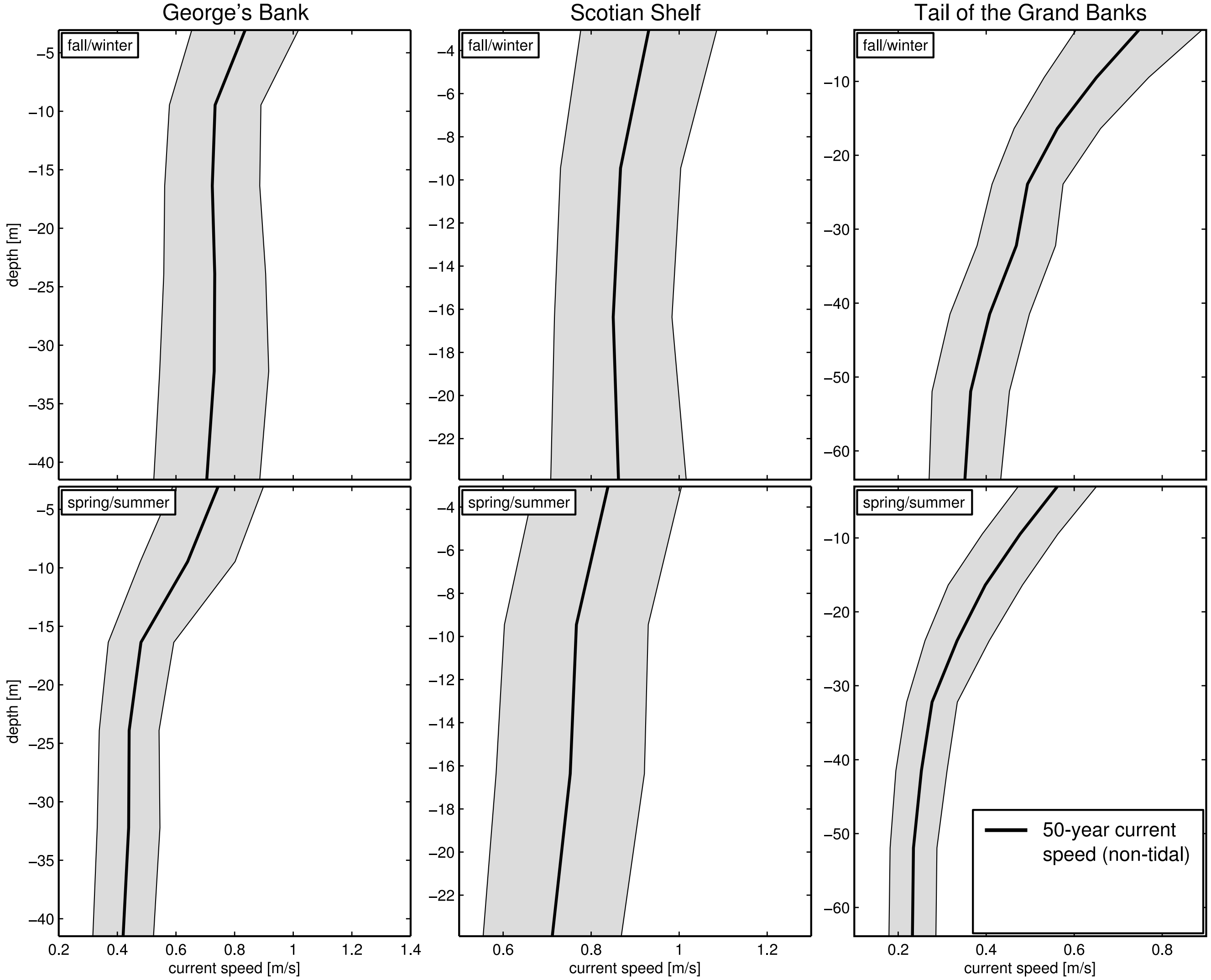

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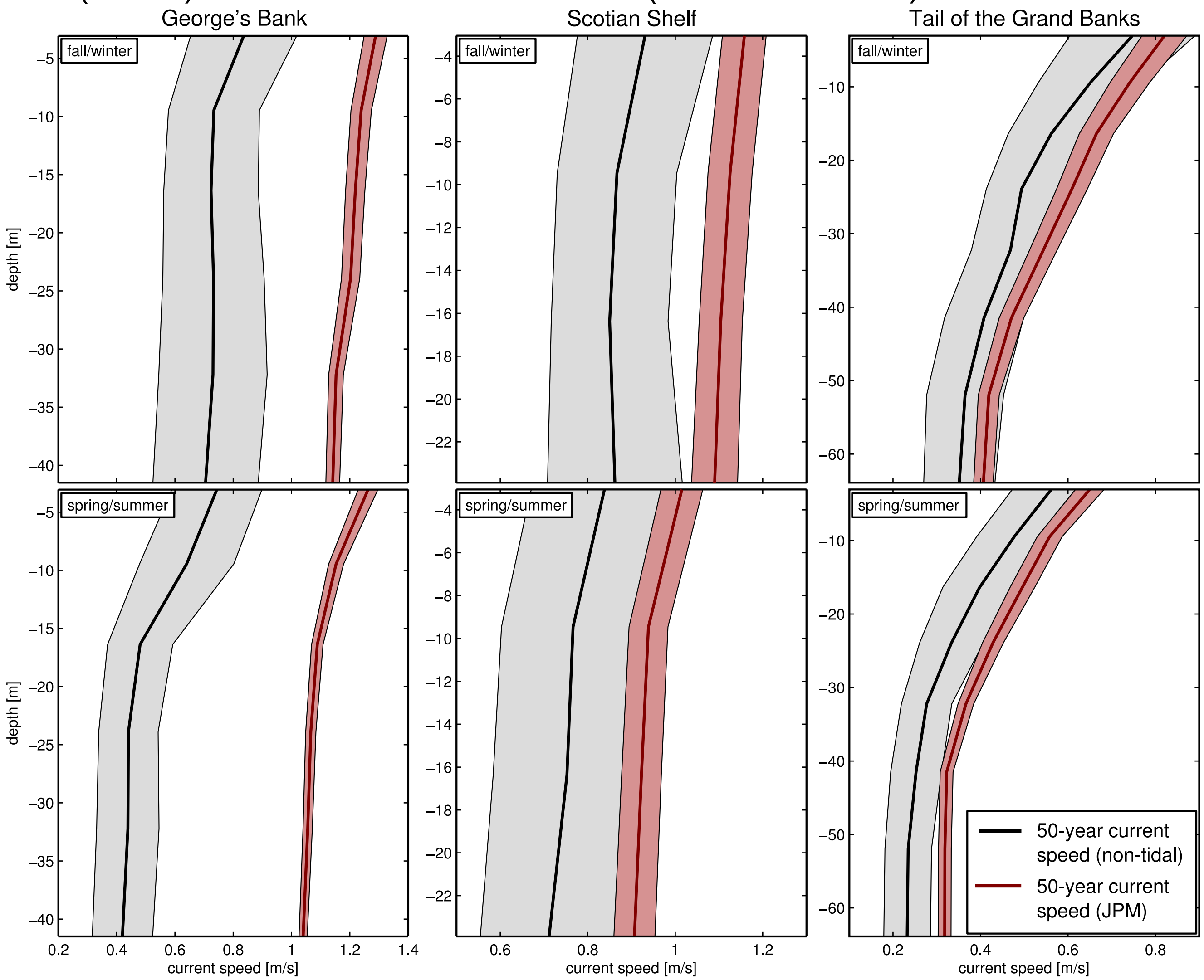


Physical Interpretation

- The geographic patterns of extreme currents given above are interpreted in terms of **simple physical principles**:

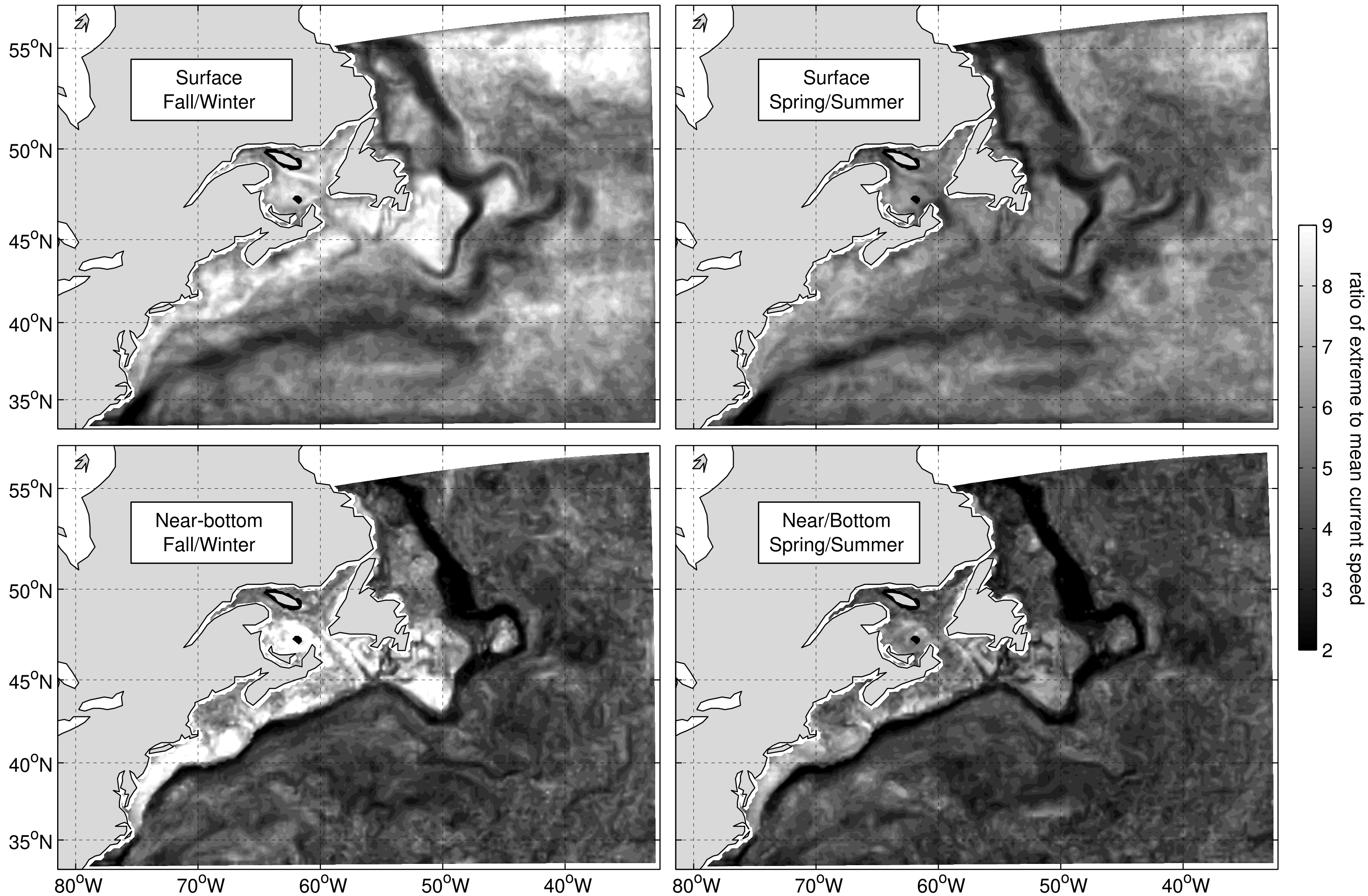
1. variability about the background flow

2. response to surface wind forcing

3. flow along isobaths

Variability About Background Flow

- Ratio of 50-year extreme currents (non-tidal) to time-mean flow



Wind-Driven Flow

- The **wind-driven currents** at the surface and near the bottom can be estimated using steady-state **Ekman theory**:

$$ifU_e = \frac{\partial}{\partial z}\left(\mu \frac{\partial U_e}{\partial z}\right)$$

vertical mixing coef.

where $U_e = u + iv$, and is subject to the **boundary conditions**

surface stress $\tau^s = \tau^s_x + i\tau^s_y$

$$\mu \frac{\partial U_e}{\partial z} = \frac{\tau^s}{\rho_0} \quad \text{at } z = 0 \quad \text{(surface)}$$

$$\mu \frac{\partial U_e}{\partial z} = rU_e \quad \text{at } z = -H \quad \text{(bottom)}$$

linear bottom friction coef.

Wind-Driven Flow

- The **solution** is given by:

water depth

$$U_{\mathrm{e}} = \alpha_1 \frac{\cosh((1+i)(H+z)/\delta_{\mathrm{E}}) + \alpha_2 e^{-i\pi/4} \sinh((1+i)(H+z)/\delta_{\mathrm{E}})}{\sinh((1+i)H/\delta_{\mathrm{E}}) + \alpha_2 e^{-i\pi/4} \cosh((1+i)H/\delta_{\mathrm{E}})}$$

(...holy crap...)

where $\alpha_1 = \tau^{\mathrm{s}} \delta_{\mathrm{E}} e^{-i\pi/4} / \sqrt{2}\mu\rho_0$

and $\alpha_2 = r\delta_{\mathrm{E}}/\sqrt{2}\mu$

Ekman depth

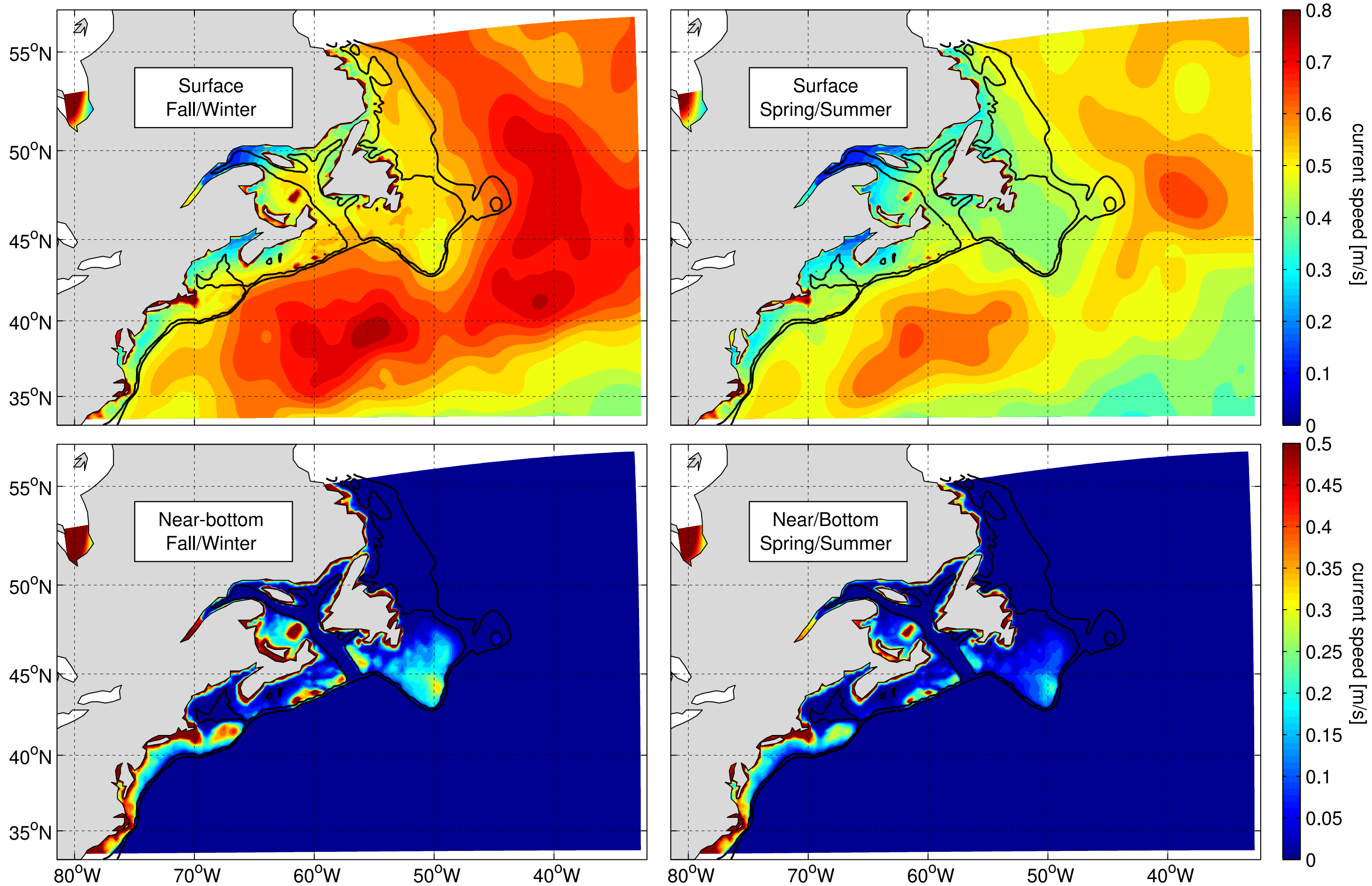
- The **Ekman depth** and **vertical mixing coefficients** are calculated from

$$\delta_{\mathrm{E}} = 0.1\sqrt{\tau^{\mathrm{s}}/\rho_0}/f \quad \text{and} \quad \mu = \delta_{\mathrm{E}}^2 f/2$$

[Csanady, 1982]

Wind-Driven Flow

- Model each grid point **independently** using steady-state Ekman theory
- Use 50-year **extreme wind-stress** (stress from Large and Pond '81 formula)



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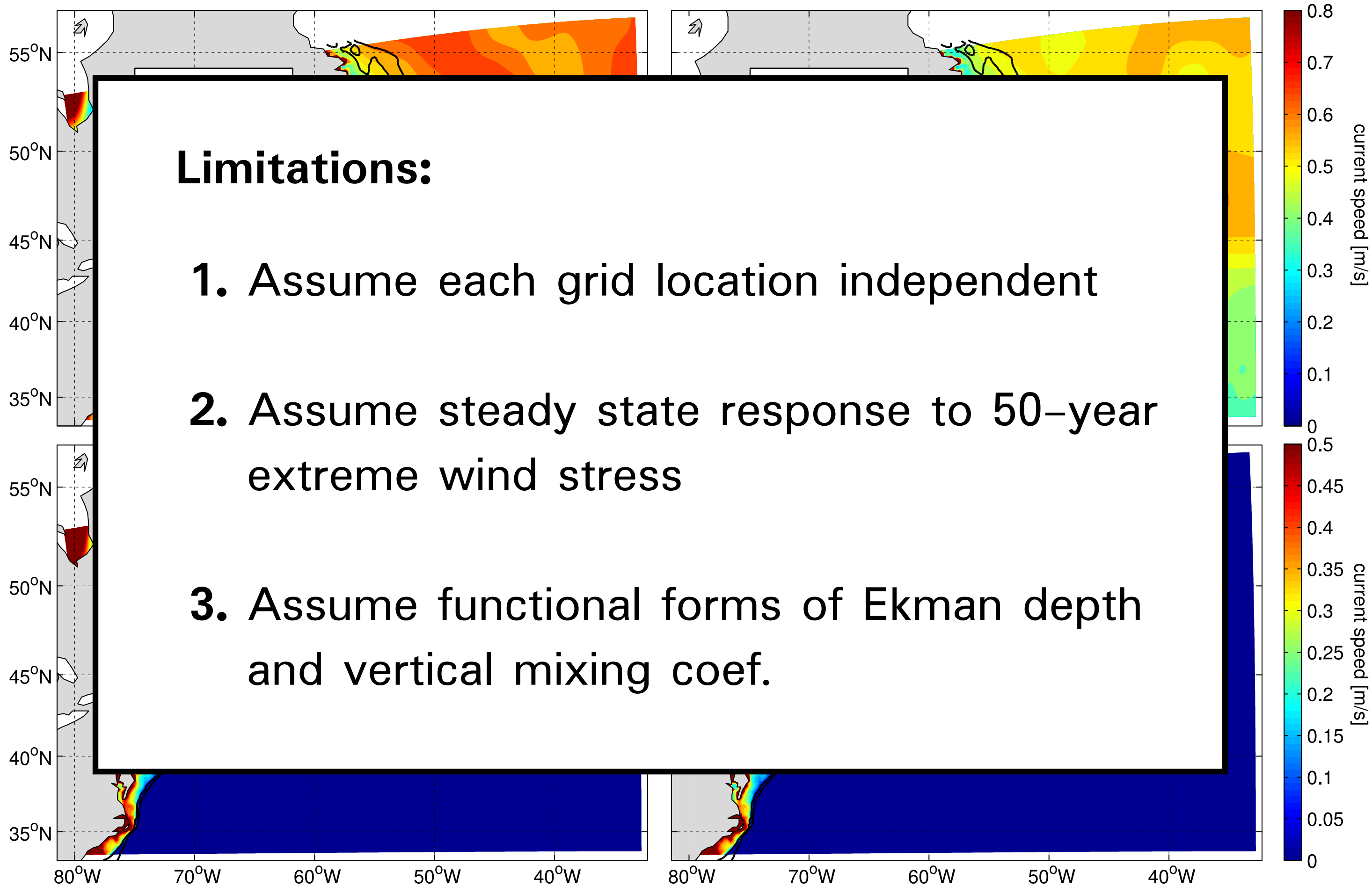
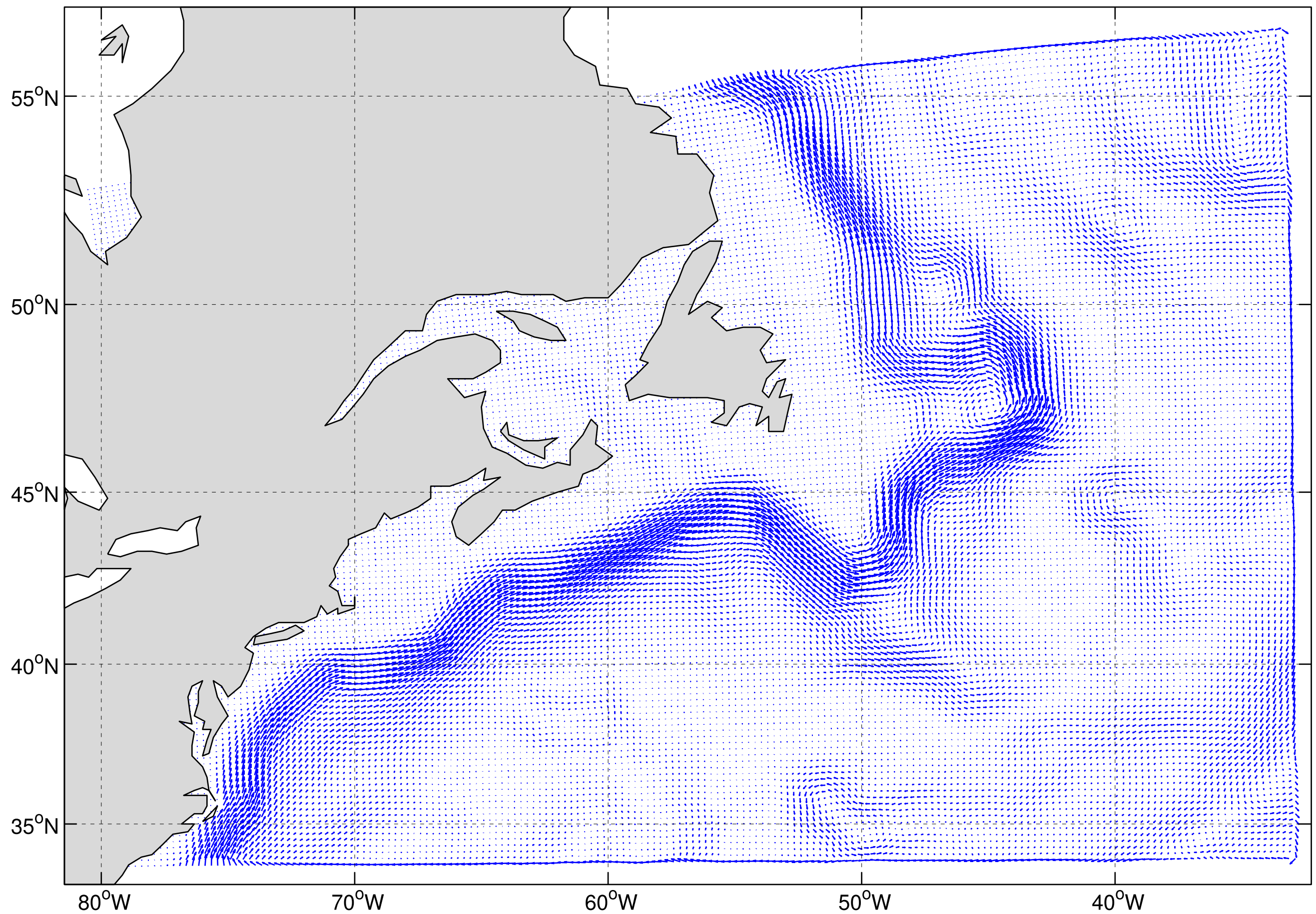


Limitations:

1. Assume each grid location independent
2. Assume steady state response to 50-year extreme wind stress
3. Assume functional forms of Ekman depth and vertical mixing coef.

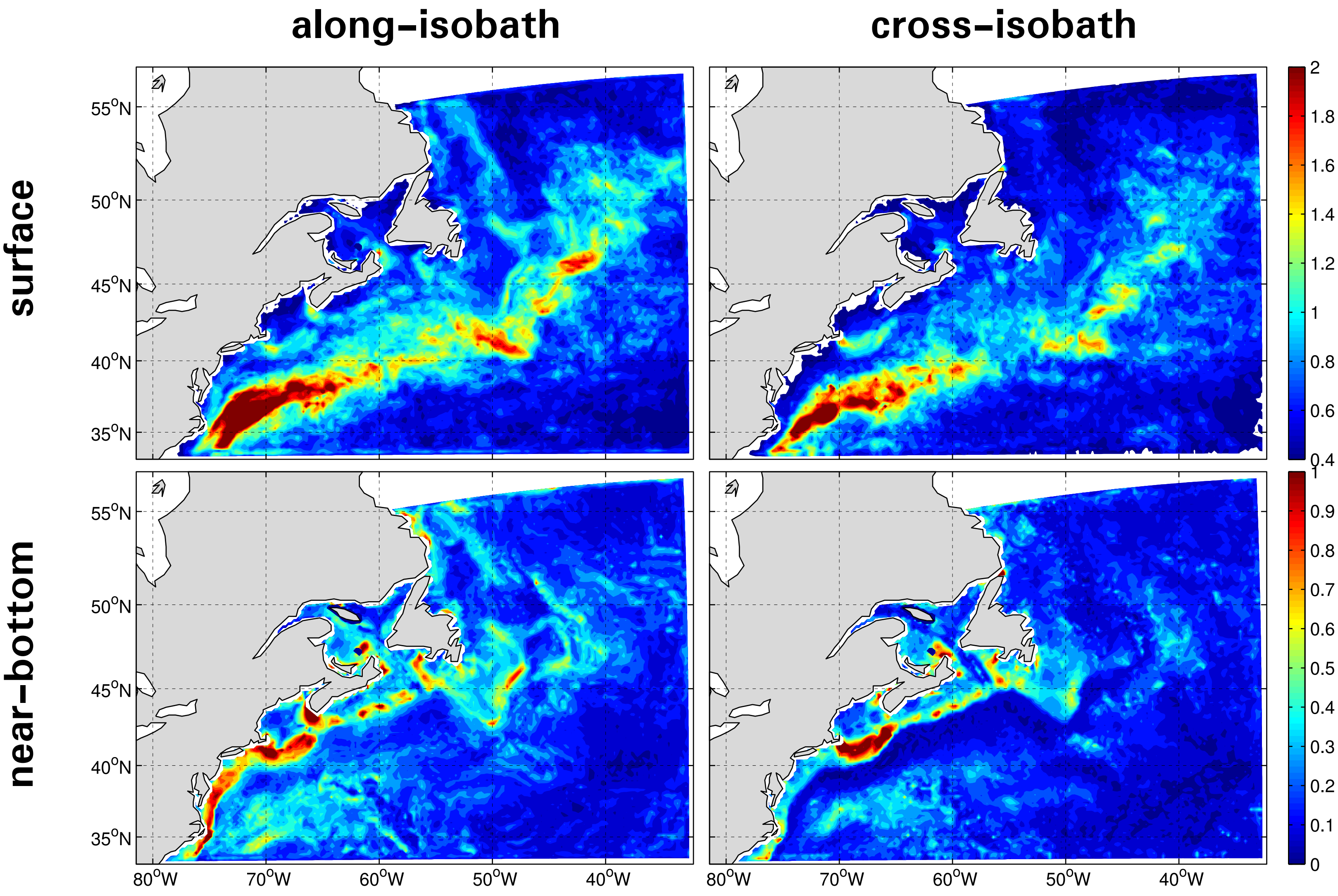
Along- and Cross-isobath Flow

- The flow may be strongly constrained by **bathymetry**
- Bathymetry is **smoothed** with a uniform 7x7 box and then calculate the **gradient** to get along– and cross–isobath vectors



Along- and Cross-isobath Flow

- Project *u* and *v* onto these vectors and calculate 50-year extreme current speeds **componentwise**



Summary and Conclusions

- We have used a three-dimensional general circulation model, along with tidal predictions, to **describe and map extreme currents** in the Northwest Atlantic

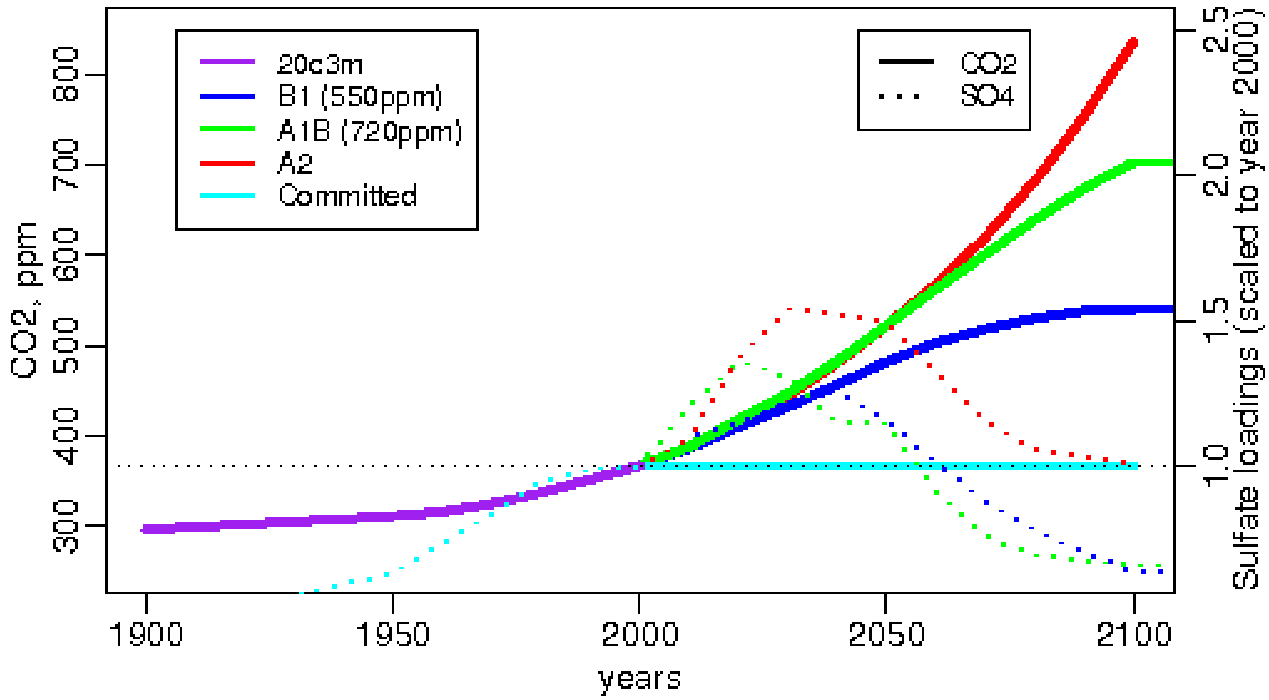
- Extreme currents were mapped for **17-year** and **50-year** return-periods and the **role of tides** was examined along three transects and for three depth profiles.

- **Seasonal changes** were also examined by performing the analysis independently on fall/winter and spring/summer.

- Finally, the extreme currents are **interpreted physically** in terms of (i) the background flow, (ii) wind-driven currents, and (iii) the steering of flow along lines of constant bathymetry.

Future Work

- Extreme currents in a projected **future climate**?
- **Idea**: run model with forcing fields that represent a possible future climate (B1?) and examine the extreme currents



- Are the extreme currents **stronger**? **Weaker**? Does the **spatial pattern change**?

  ..... this is being undertaken now