The Vertical Structure of the Baroclinic Tidal Currents: assessing the skill of a global ocean model

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Objective

- Assess performance of forward tide calculation in global HYCOM compared to existing current meter records
  - Develop a skill test to assess model performance
    - At a single current meter record
    - Over an entire mooring record (by depth)
    - Over a geographic region (identified seas, abyssal plains, coastal regions)
- Important Considerations:
  - Available observations are sparsely distributed in time and space
  - Existing Current meter records vary in duration and quality
  - Older mooring locations (pre-GPS) leads to position uncertainty
  - Model bathymetry may not be true
  - Grid limits representation of ocean fronts and atmospheric forcing
  - Global model runs at 1/12° are computationally expensive

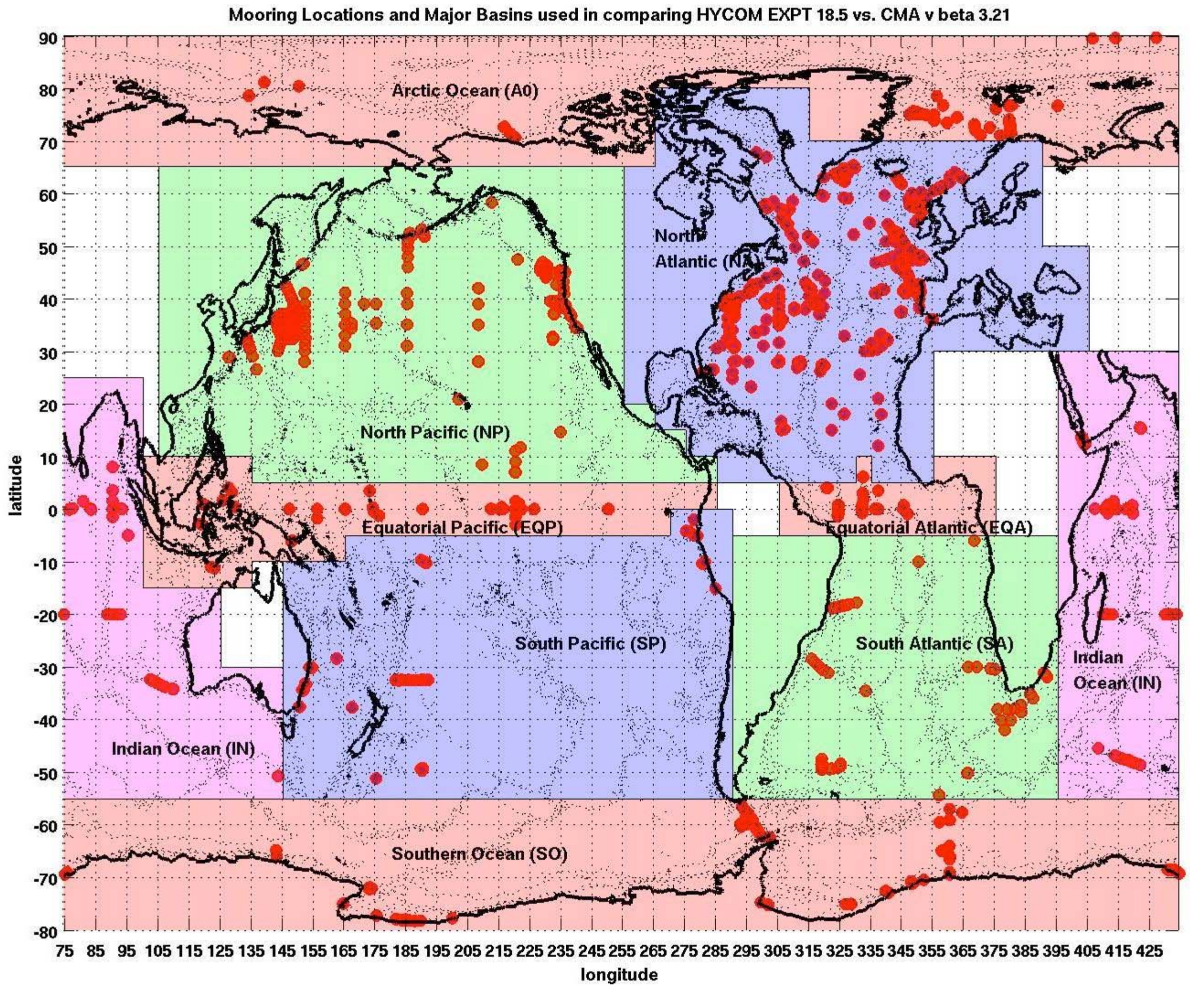
Method

- An ensemble of model runs is not feasible
  - True horizontal and vertical density structure for a given year and region is not known on a global scale
  - Sparse distribution of observations does not provide means of assessing the global tides on a year by year basis
  - We have limited model data due to computational constraints and data storage capacity.
    - e.g. 30 days of hourly model output ~8 Terabytes
- Optional approach: Create distributions from the observations at each instrument to produce statistical comparisons:
  - Local Skill Tests
    - Instrument level
    - Mooring level
  - Regional Skill Tests

Selection of Current Meter Records

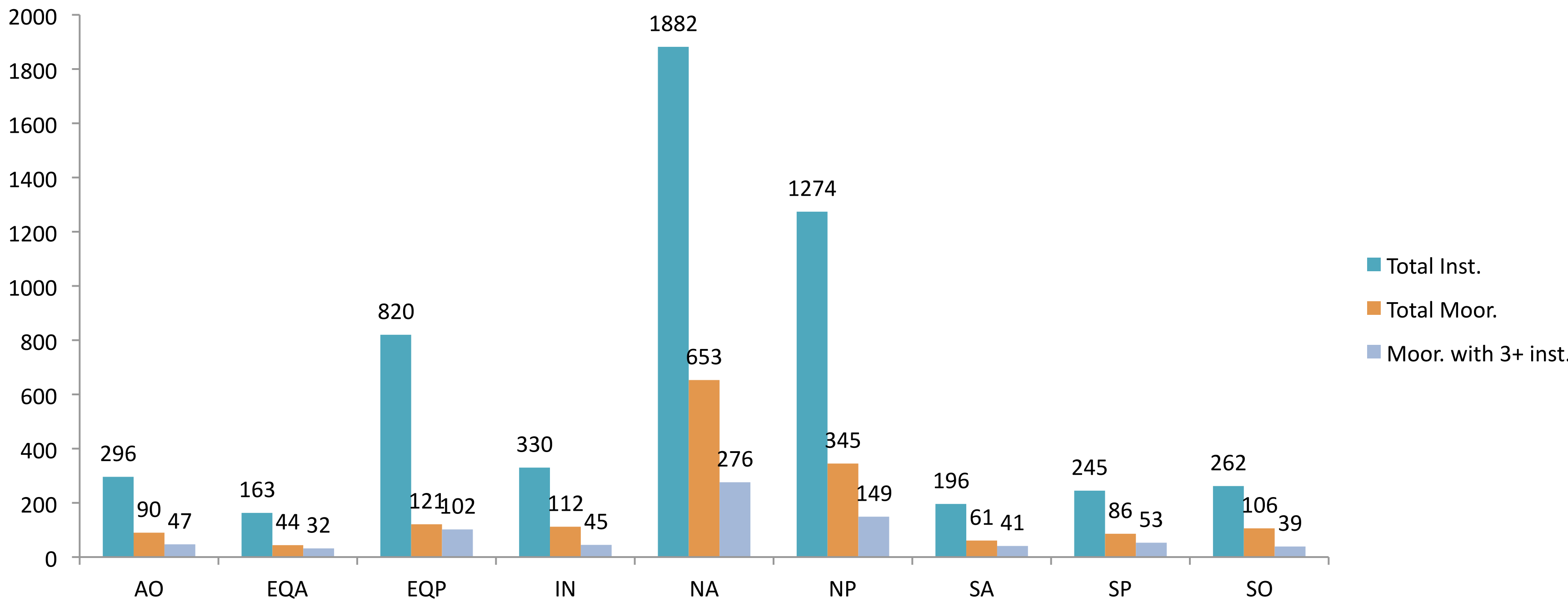
- Record selection criteria:
  - Moorings with at least 3 instruments
  - Observation interval:
    - hourly or more frequent observation intervals
  - Length of Record:
    - Minimum 105 days
      - May be 105 days continuous observations
      - At least 6 – 30 day windows for non-continuous observations

Distribution of Observations

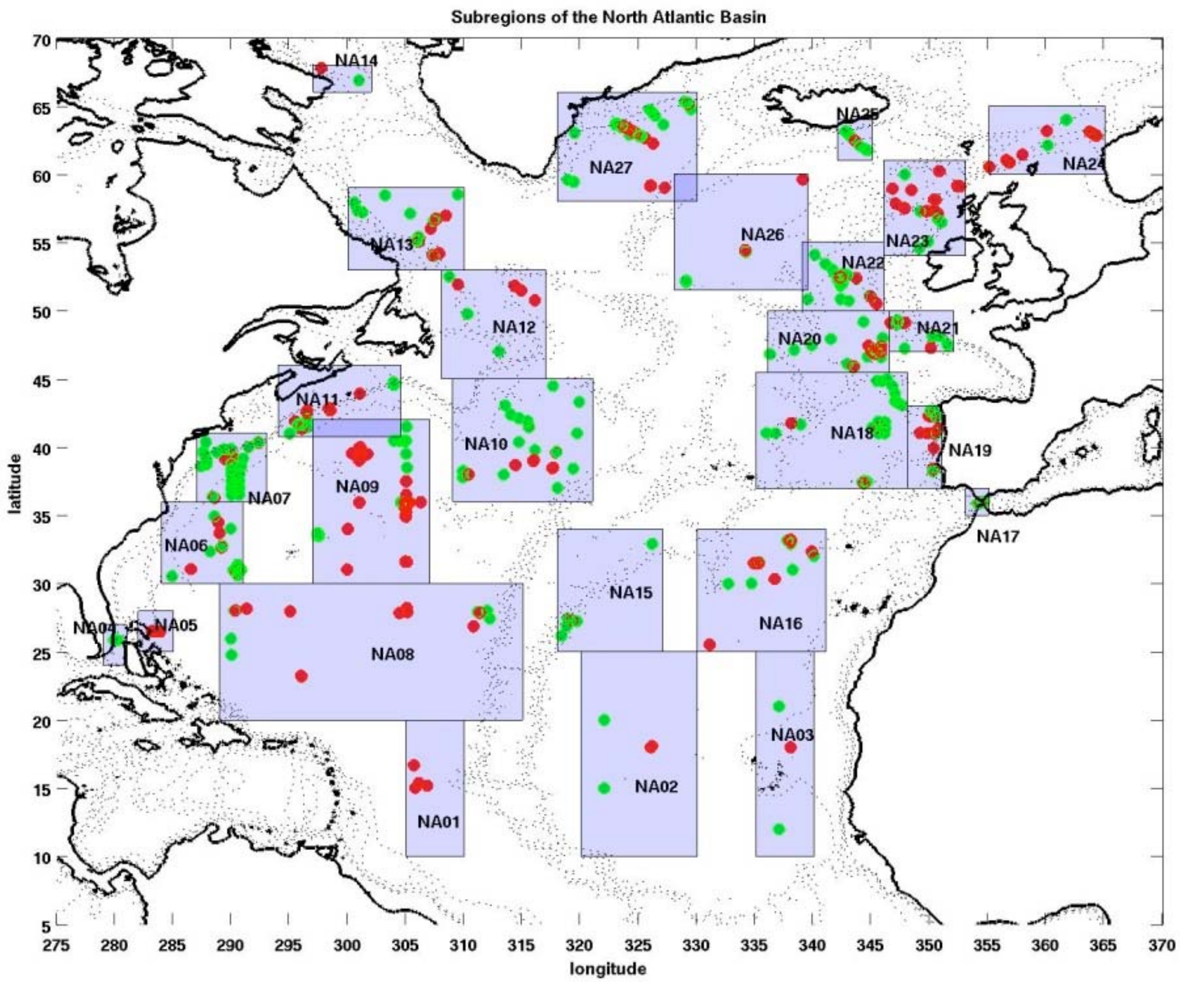


Mooring Archive

- 5468 velocity records
  - 1618 Moorings
  - 784 Moorings with 3 or more velocity records



North Atlantic Sub-regions



Moorings are grouped into 27 sub-regions within the North Altantic

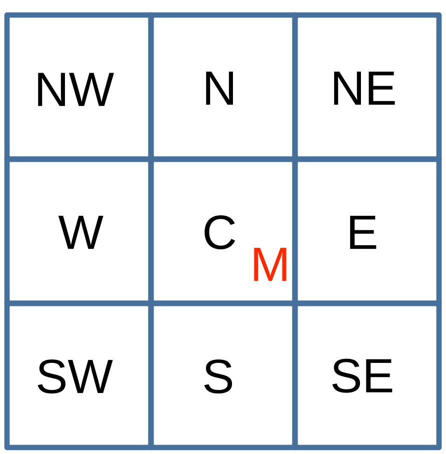
Grouping attempts to divide moorings into groups representing coastal, slope and shelf regions within geographic areas

Harmonic Analysis of the Current Meter Records

- Observations are subdivided into 30 day windows overlapping by 15 days
- Each window high pass filtered
  - removes secular trends
  - retains frequencies above diurnal frequency range
- Each 30 day window is subjected to harmonic tidal analysis
- Produces a distribution of estimates for the tidal constituents M_2, S_2, N_2, K_1, O_1, Q_1 at each instrument.

Selection of HYCOM data

- Nearest Neighbour Approach
  - Determine the model grid cell nearest the mooring location (**nearest neighbour**)
  - Choose the 3 x 3 block of model cells the contain the nearest neighbour in the middle (**neighbourhood**)
  - Allows for uncertainty in mooring location and model bathymetry

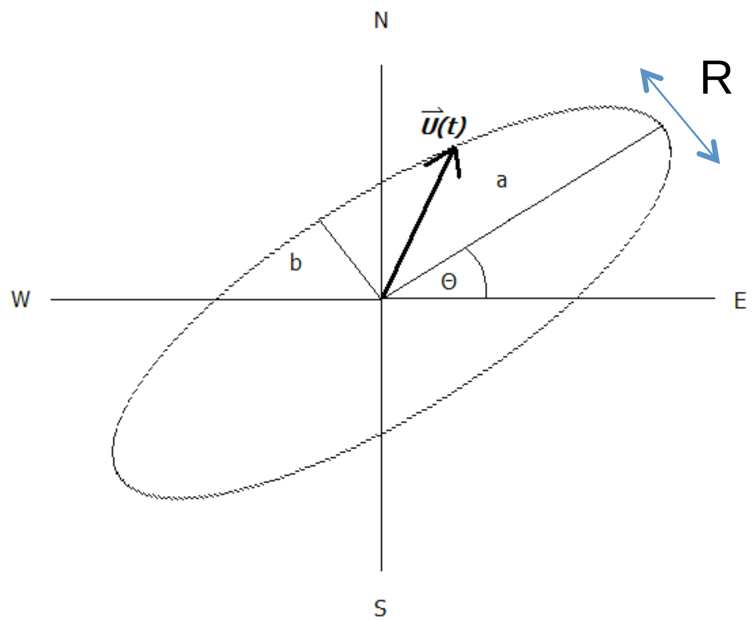


Mooring is located at position M

Nearest Neighbour is grid: C

Other neighbours identified by direction from C

Tidal Current Ellipses



The tidal ellipse may be described by 5 parameters:

a – semi-major axis
b – semi-minor axis
Θ – inclination
G – Greenwich Phase
R – direction of rotation

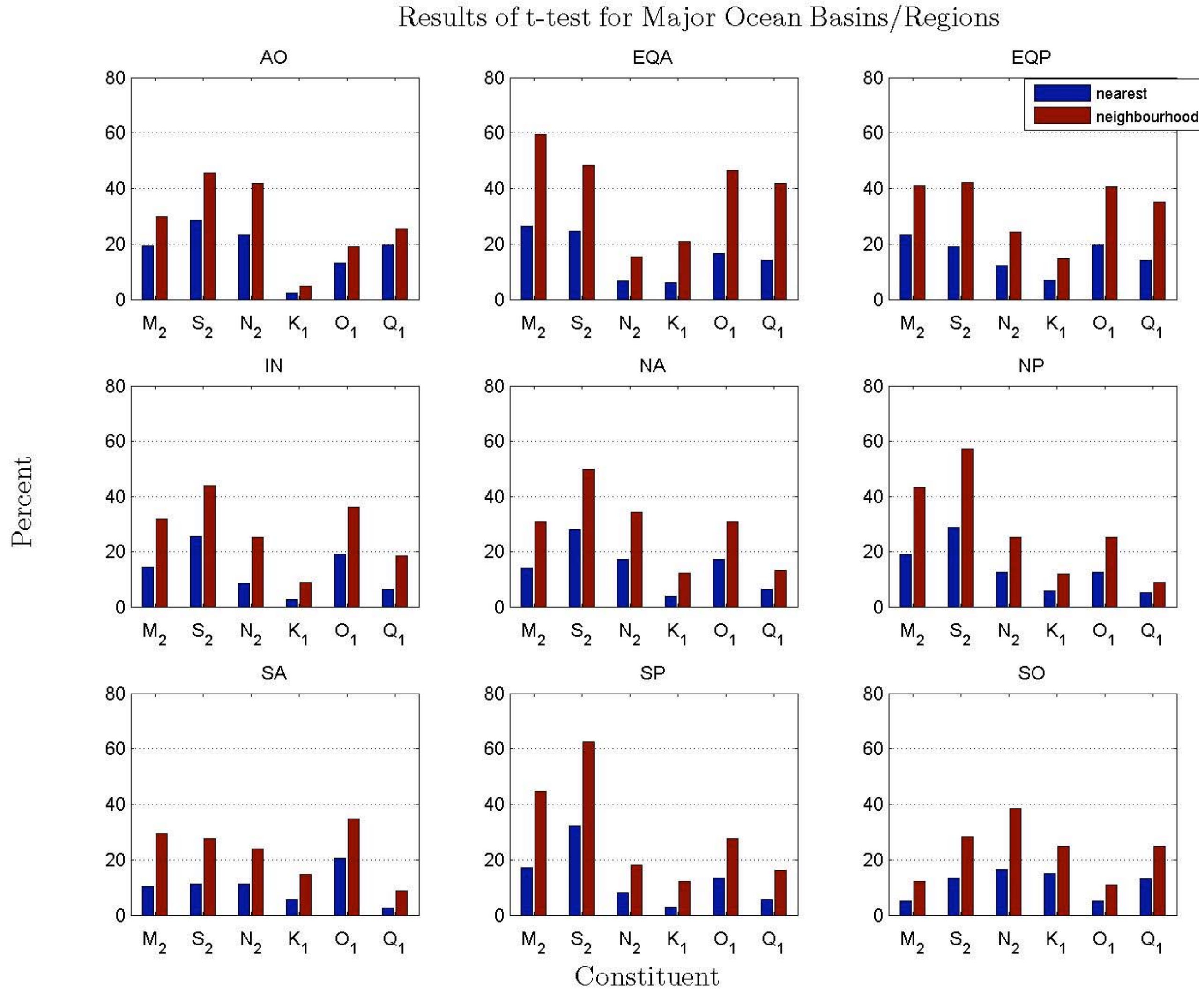
The **inclination** refers to the angle between the northward oriented semi-major axis and the east compass point hence $0 \leq \Theta \leq 180°$

The **Greenwich Phase** refers to the time of maximum current measured from the northward oriented semi-major axis 15° = 1 hour lag referenced to Greenwich

Instrument level skill test #1

- Parametric Test
  - Tidal ellipse semi-major axis estimated at each model z-level (interpolated from model layers) is interpolated to the depth of the instrument
  - Null Hypothesis:
    - $H_o: \frac{1}{N} \sum_{n=1}^{n=N} (A_{obs(n)} - A_{mod}) = 0$
  - Assumes the windowed observations are independent and normal

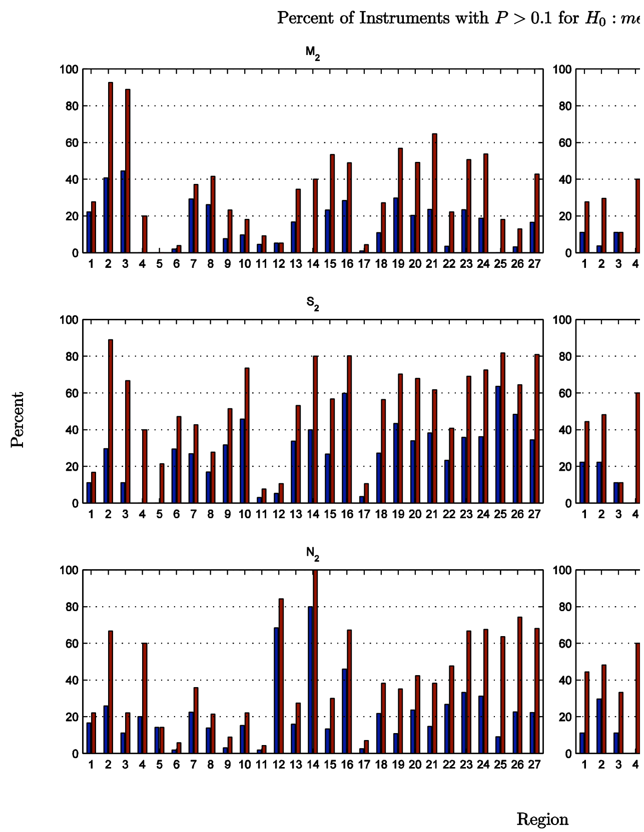
Percent Non-Rejection of Null Hypothesis Nearest Neighbour vs. Neighbourhood



Graph shows the percentage of all instruments in each basin for which the null hypothesis: H_0: $\sum(a_{obs}(n) - a_{mod})/N = 0$ with $P > 0.1$ using 95% confidence intervals.

For an instrument neighbourhood the null hypothesis is satisfied if the null hypothesis is not rejected in at least one of the 9 neighbours.

North Atlantic: Nearest Neighbour vs. Instrument Neighbourhood

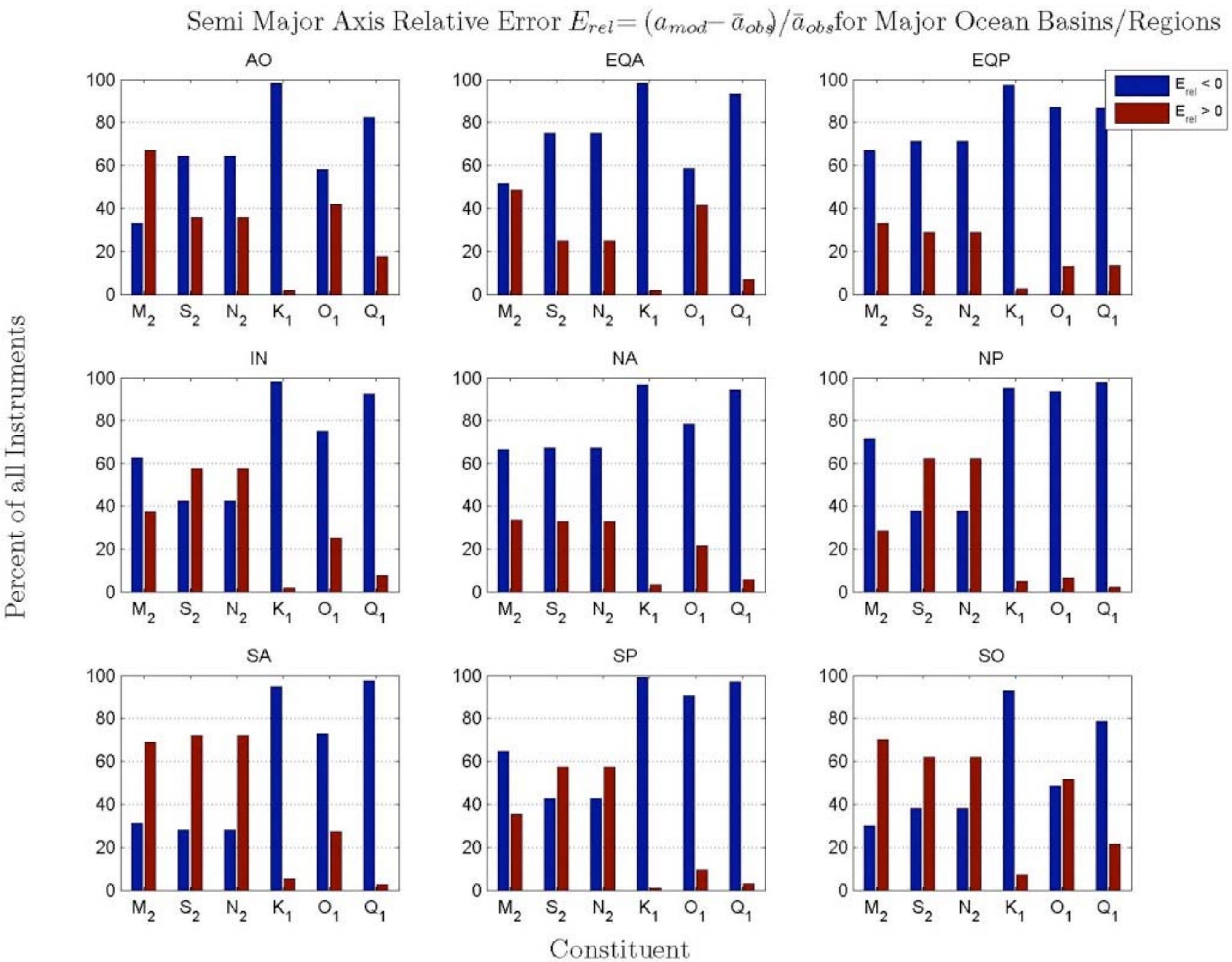


Bar Graph represents the percent of all instruments within each sub-region that do not reject the null hypothesis at the nearest neighbours and within a 9-point instrument neighbourhood.

We consider the null hypothesis to not be rejected within a neighbourhood if it is not rejected at a least one instrument neighbour.

Notes:
For the semi-diurnal constituents the rate of non-rejection is typically 40 – 80% within a neighbourhood.
For diurnal constituents the rate of non-rejection is only 0 – 40%

Semi-major Axis Relative Error



$$E_{rel} = 100 * \frac{(a_{mod} - \bar{a}_{obs})}{\bar{a}_{obs}}$$

$E_{rel} < 0$

$E_{rel} > 0$

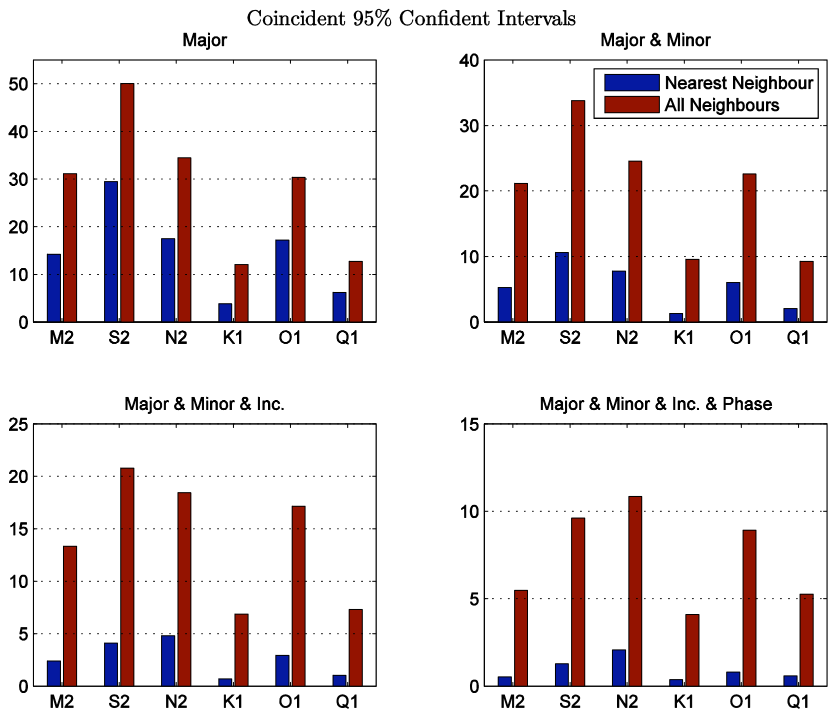
Diurnal Const. K_1, O_1 and Q_1 weak compared to observations

Semi-Diurnal Const. M_2, N_2, S_2 are mixed within different basins

Instrument level skill test #2

- Non Parametric Test (Preferred)
  - Construct 95% Bootstrapped confidence intervals (Bias Corrected and accelerated) using 2000 bootstrapped replicates for semi-major and semi-minor axis of windowed observations
    - (Efron and Tibshirani, 1993)
    - Determine if the model value lies within the 95% confidence interval of the observed mean value
  - Construct 95% confidence intervals for ellipse inclination and the Greenwich Phase
    - circular statistics (Fisher, 1995)
  - Look for Coincident Positive Outcomes ie. Model value lies within confidence intervals

North Atlantic: Coincident Positive Outcomes



Semi-major and Semi-minor axis:

- Kinetic energy
- KE ~ (a^2+b^2)

Semi-major/minor and Inclination:

- Principal Axis

Semi-major/minor, Inclination Phase:

- Time of Maximal Flow along semi-major axis

Instrument Level Skill Test #3

Calculate the Root Mean Square Error at each of the 9 grid cells between the interpolated model value and the windowed observations

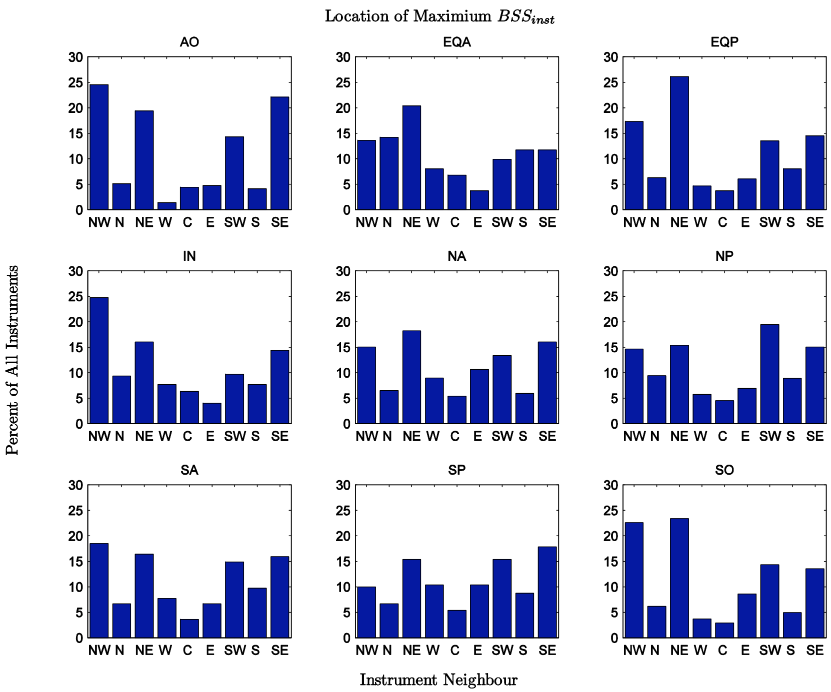
$$RMSE_{inst} = \sqrt{\frac{1}{N}\sum_{n=1}^{n=N}(a_{obs}(n) - a_{\mathrm{mod}})^2}$$

Use Brier Skill Score:

$$BSS_{inst} = 1 - \frac{RMSE_{inst(neighbour)}}{RMSE_{inst(nearest)}}$$

To find neighbour with best fit to observations at **all** instruments in the global mooring archive

Instrument Best Fit for Ocean Basins



Expected Value for Random Error is 1/9 or 11%

Instrument Best fit appears to prefer Corner Neighbours

One possible explanation is the interpolation scheme used to interpolate velocity data on the Arakawa C-grid to Pressure Points

Mooring Level Skill Test #1

- Calculate Mooring Root Mean Square at each mooring:

$$RMS_{moor} = \sqrt{\frac{1}{K}\sum_{k=1}^{k=K}(RMSE_{inst}(k))^2}$$

($RMS_{moor} \equiv RMSE_{inst}$ for $K = 1$)

- Applied to moorings with 3 or more instruments only

Mooring Level Skill Test #2

- Correlation Skill Score:

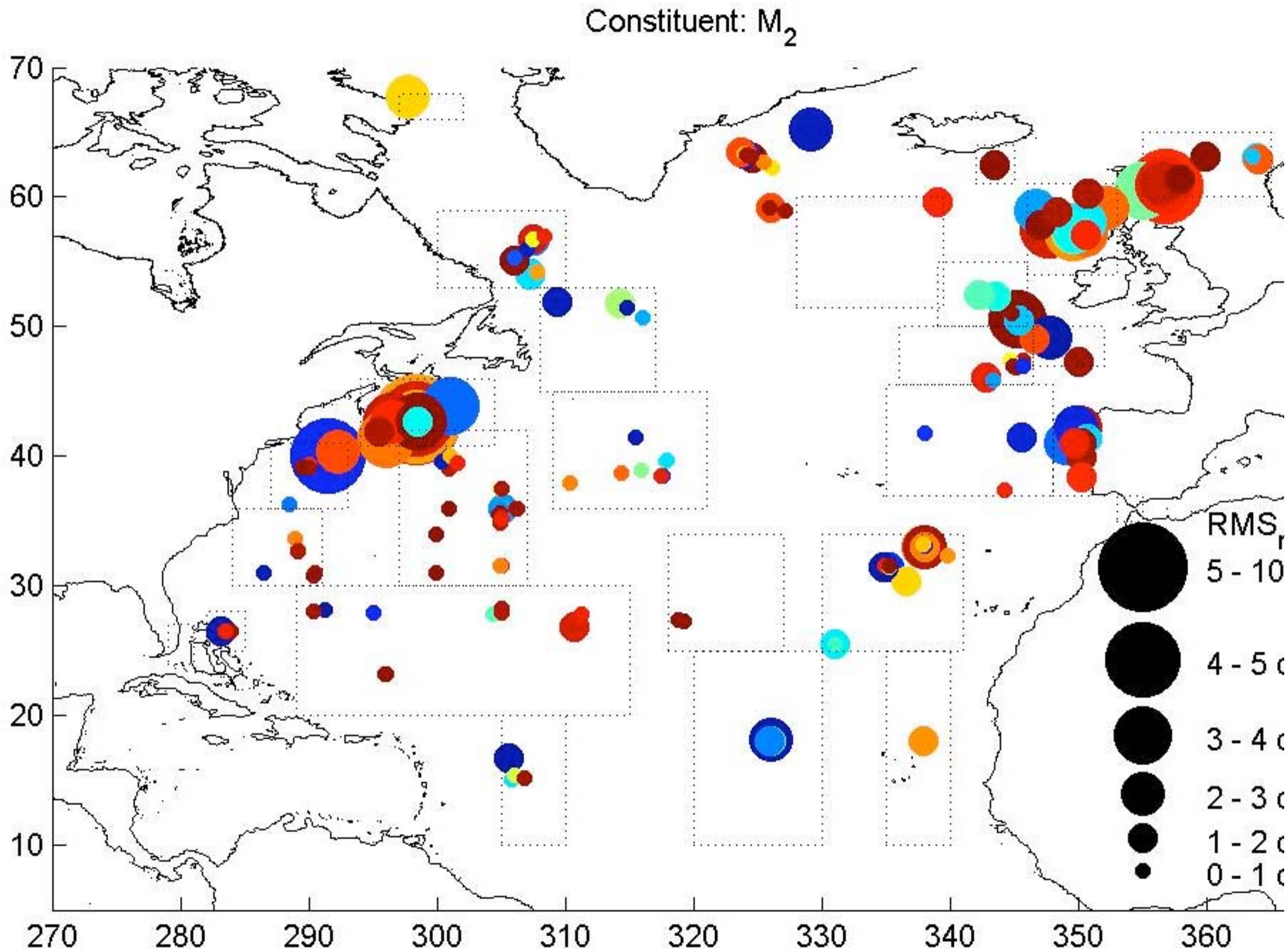
$$CSS_{moor} = \frac{Cov(A_{mod}, \bar{A}_{obs})}{(\sqrt{var(A_{mod})}\sqrt{var(\bar{A}_{obs})}}$$

Estimate the correlation coefficient between the instrument levels and corresponding interpolated model values:

$$-1 < CSS_{moor} \leq 1,$$

Translation invariant but provides information on how well the vertical profile of the model data matches the vertical profile of the observed currents

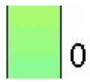
M_2 Mooring Skill – North Atlantic



Mooring RMS is represented by the size of the circle

Mooring CSS is represented by its colour. Red indicates high correlation, blue is negative or no correlation

Generally higher RMS values occur in coastal regions but correlation is not tied to RMS.



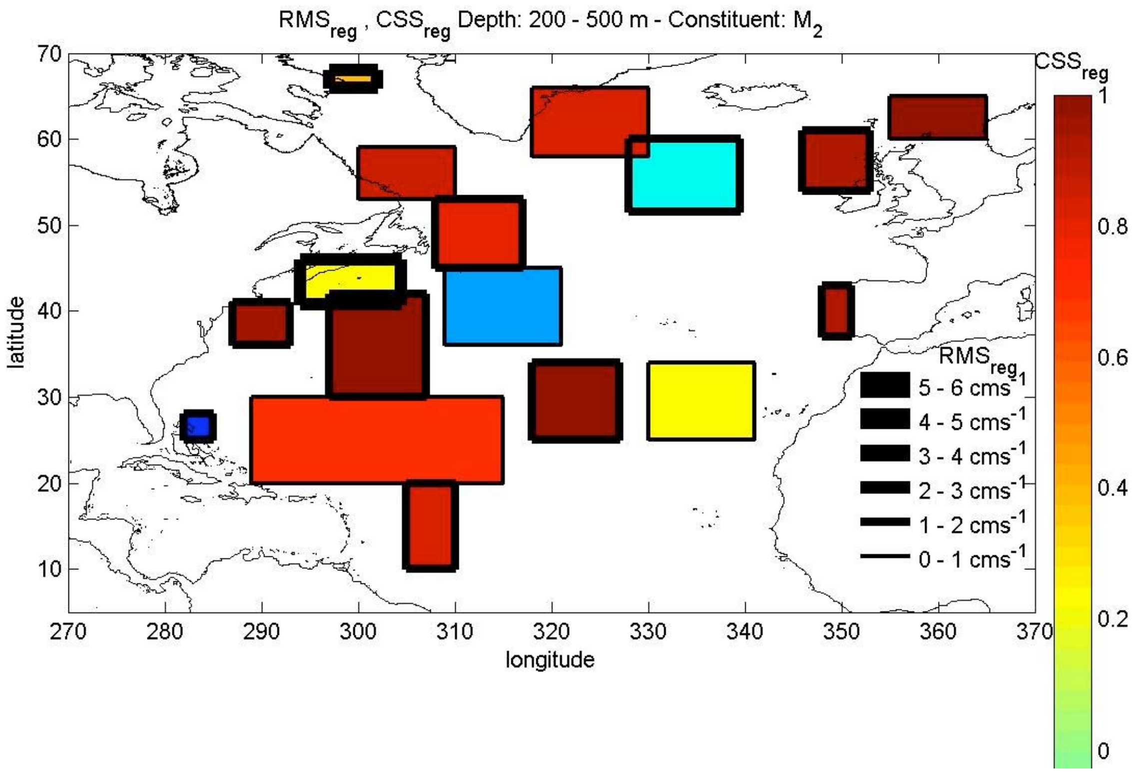
Regional Skill Tests #1 & #2

- Bin the observations by depth
- For Depth Bins with 3 or more instruments:
  - Calculate RMS_{region} and CSS_{region} using:

$$RMS_{region} = \sqrt{\frac{1}{L}\sum_{l=1}^{l=L}(RMSE_{inst(l)})\text{^}2}$$

$$CSS_{region} = \frac{cov(\bar{A}_{obs}, A_{mod})}{\sqrt{var(\bar{A}_{obs})}\sqrt{var(A_{mod})}}$$

Regional Model Skill: M_2 : 200-500 m



RMS: (not shown)

Thickness of black border indicates the RMSE, thicker the border the greater the RMSE

Correlation Coeff:

Blue: negative or no correlation

Red: positive correlation

We want red rectangles with thin borders!

Summary

- The methods presented allow for a systematic approach to assessing the model skill in reproducing observed vertical structure of tidal currents in an ocean model
- Skill tests provide an overview of model performance in the vertical and horizontal directions to highlight regions in the ocean model where bias may exist
- With NO data assimilation the model appears to perform reasonably well in regions where tidal signals are expected to be linear and have little interaction with bathymetry and coastal features. For the North Atlantic Basin
- Larger RMSE and correlation errors tend to occur in regions where the tidal signal may be more complicated by interaction with large bathymetric features and interactions with strong persistent currents