Status of Hydrodynamic models

Charine Collins
SAEON Egagasini Node

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NRF National Research Foundation | SAEON South African Environmental Observation Network

History of Ocean modelling

1960s
Bryan-Cox model

Kirk Bryan & Michael Cox published first 3D model of ocean circulation

1920s
Numerical weather prediction

1980s
Blumberg-Mellor model

Development of model that can handle high-resolution coastal ocean processes (e.g. tides)

1970s
First operational wave model

1990s
Princeton Ocean Model

First open-source model. Used for first simulation of entire Atlantic Ocean. Also used for the construction of the first ocean forecast system

2010s
Coastal ocean prediction

Move towards high-res ocean prediction systems

Move from mesoscale to submesoscale

2000s
Various σ-coordinate models, data assimilation

Move from large-scale to mesoscale

Dynamical Downscaling

Development of various terrain-following models with numerical and parameterisation improvements

Advent of data assimilation lead to improved model simulations and ocean reanalysis products

Significant progress over last several decades in model architecture and availability of computational resources.

Advances Ocean modelling

Evolution from coarse-resolution to fine resolution

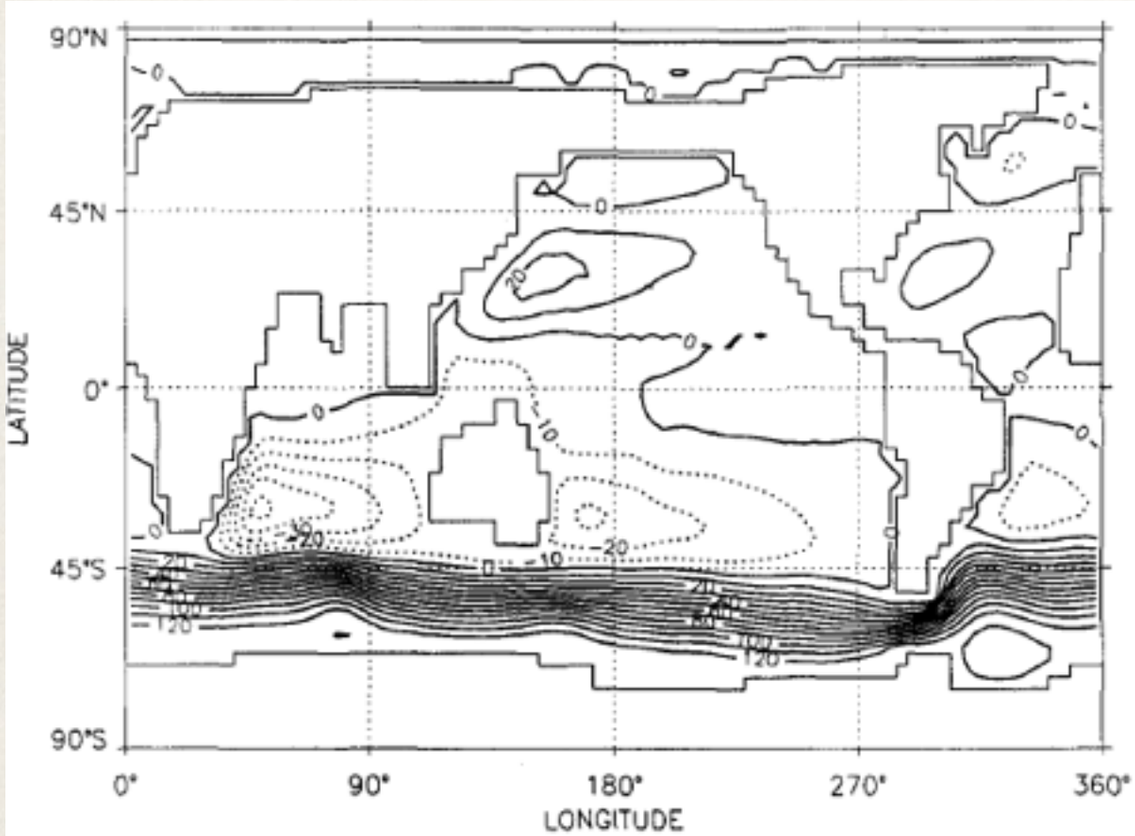


Figure 1 Time-averaged, depth-integrated horizontal transport streamfunction in Sv (1 Sv = 10^6 m^3 s^{-1}) in a coarsely resolved OGCM solution. The flow direction is clockwise around maxima. (After Danabasoglu et al 1994.)

Simple geometry and bathymetry

Realistic coastlines and bathymetry

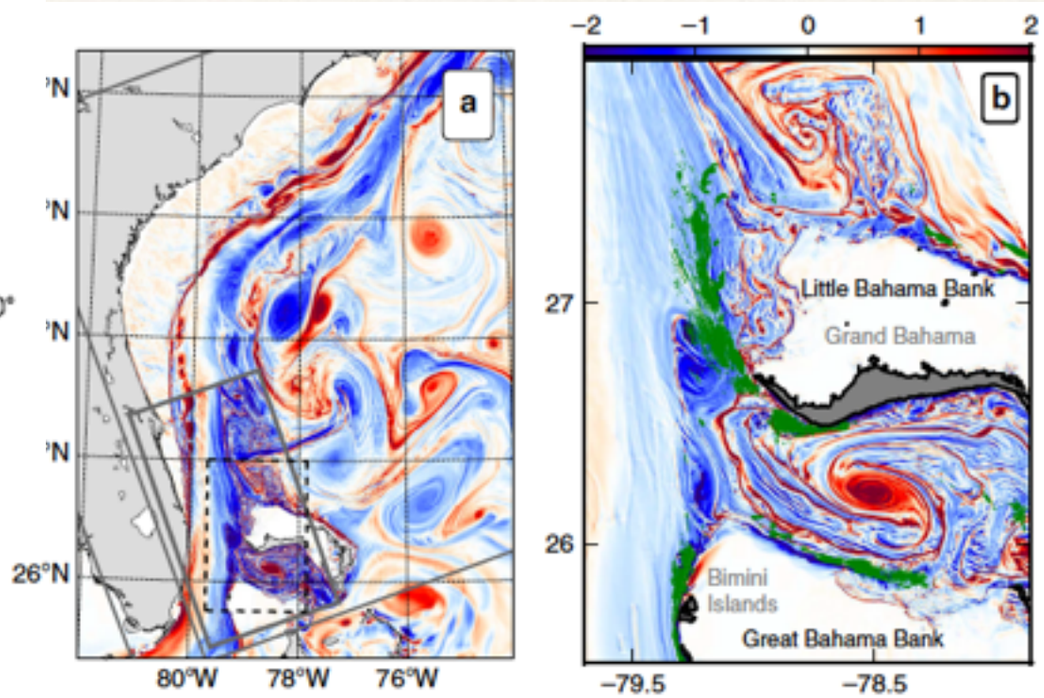


Figure 1 | Topographic generation of negative vorticity along the Bahamas Banks. (**a**) Instantaneous surface relative vorticity $\zeta = v_x - u_y$, normalized by f, for the Gulf Stream along the southeast US seaboard as simulated by ROMS. The boundaries of the successive nested domains ($\Delta x = 2.5$, 0.75 and 0.20 km) are delineated by thick grey lines. (**b**) Zoomed-in view of the Gulf Stream along the Bahamas Banks. Green contours show region of high energy dissipation (depth-integrated energy dissipation $\langle \epsilon \rangle > 2 \times 10^{-4}$ W m kg^{-1}). Localized regions with negative vorticity and high energy dissipation rates are created by the currents flowing along the topographic slopes of the Bahamas Banks.

Advances Ocean modelling

Evolution from coarse-resolution to fine resolution

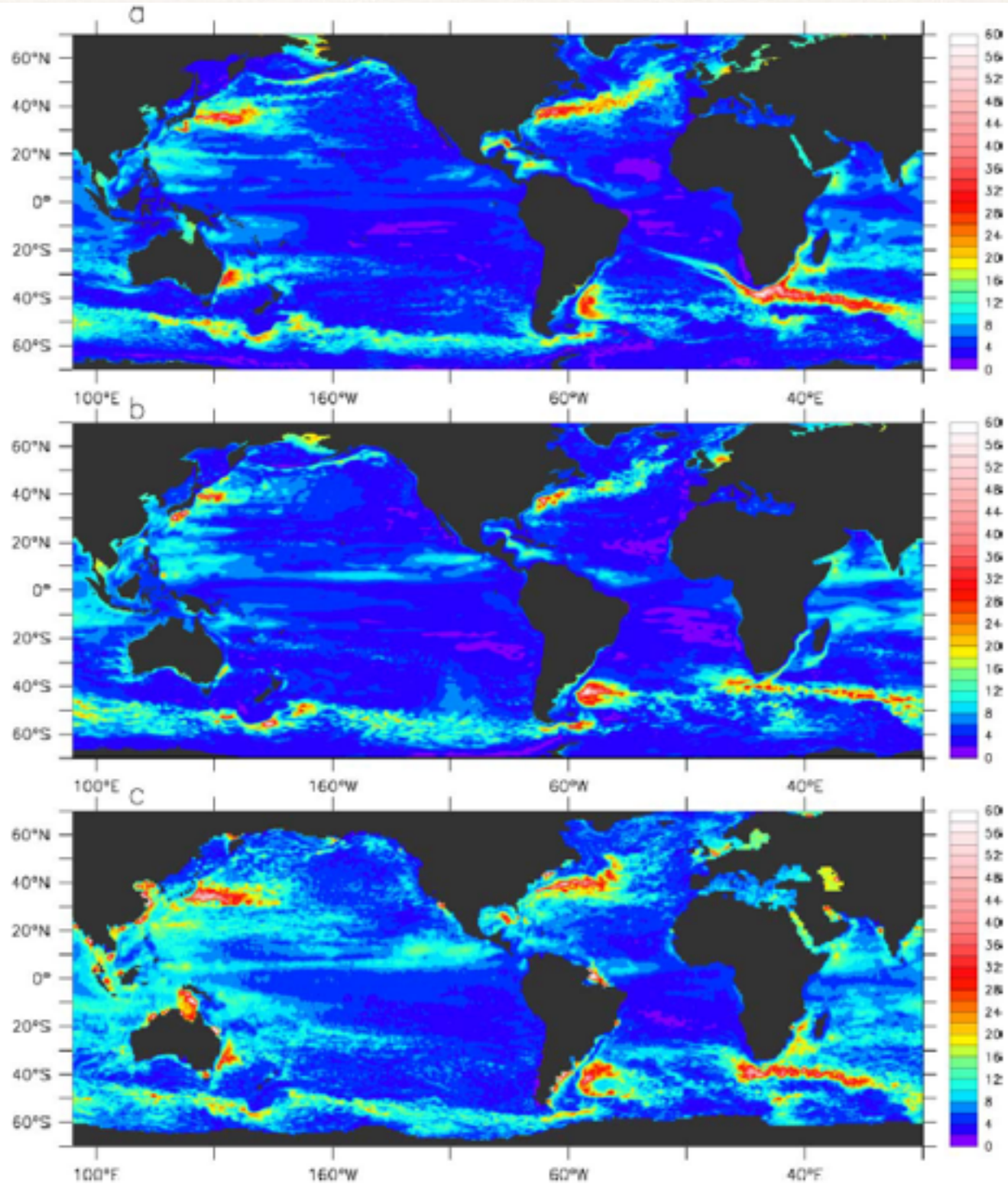
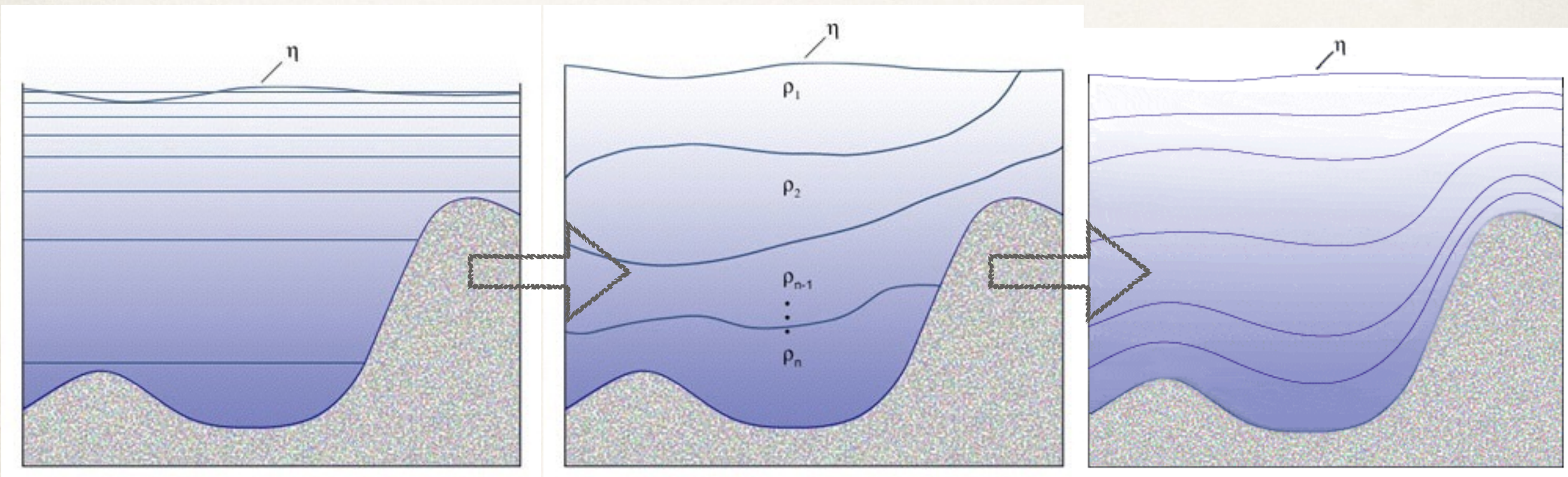


Fig. 12. Sea surface height variability (cm) from (a) the 1/10° model for 1991–1993 (b) 0.28° model for 1995–1996 and (c) TOPEX-ERS1 for 1995–1997 (Ducet et al., 2000).

Advances Ocean modelling

Vertical coordinate system



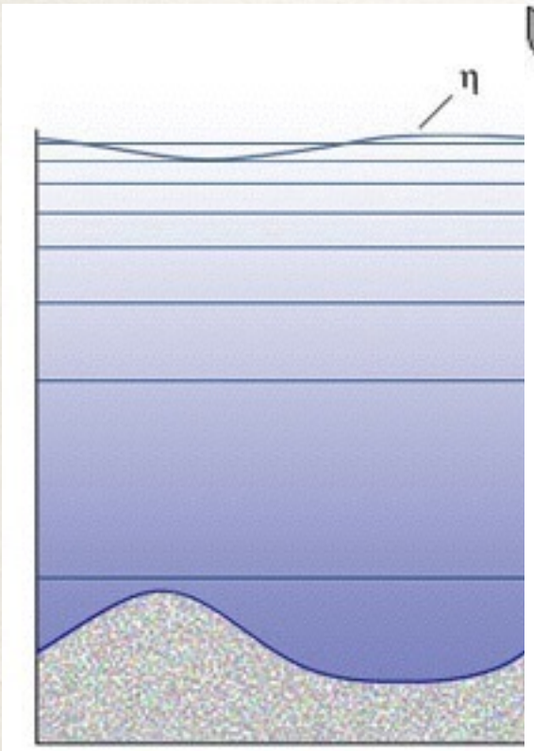
levels at fixed depth (z-level) are best for high resolution near surface

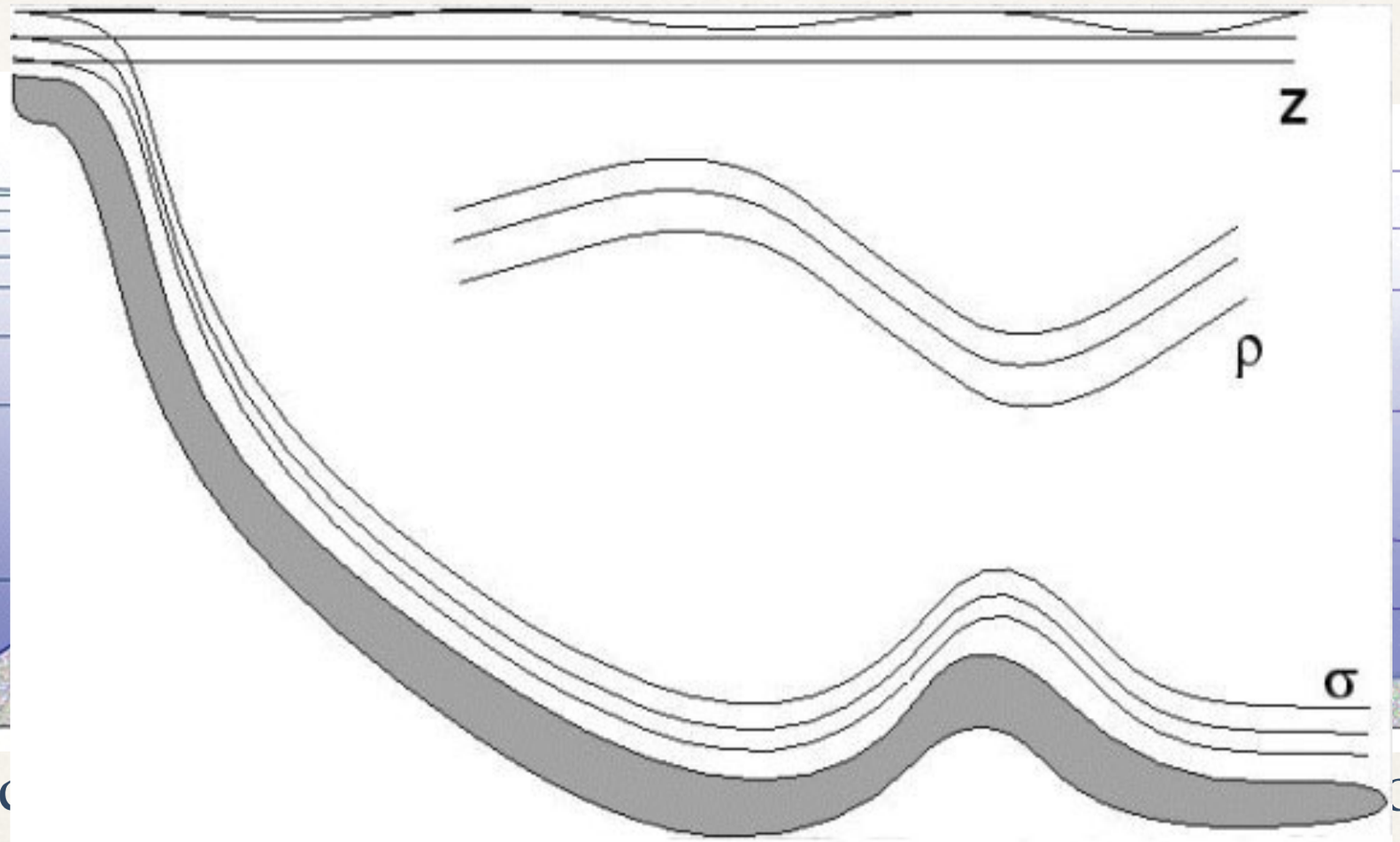
isopycnic (density-tracking) layers work best for deep stratified ocean

terrain-following (σ) layers are best choice for shallow coastal regions

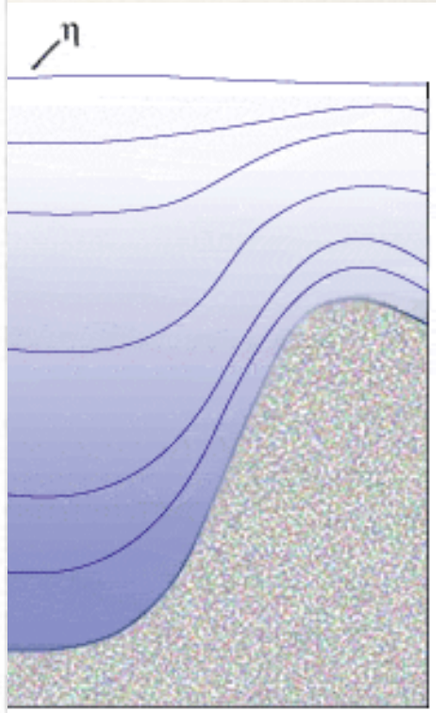
Advances Ocean modelling

Vertical coordinate system





1 Courtesy – Prof. Eric Chassignet (U. Miami)



levels at fixe

(z-level) are

high resolution near surface

work best for deep stratified ocean

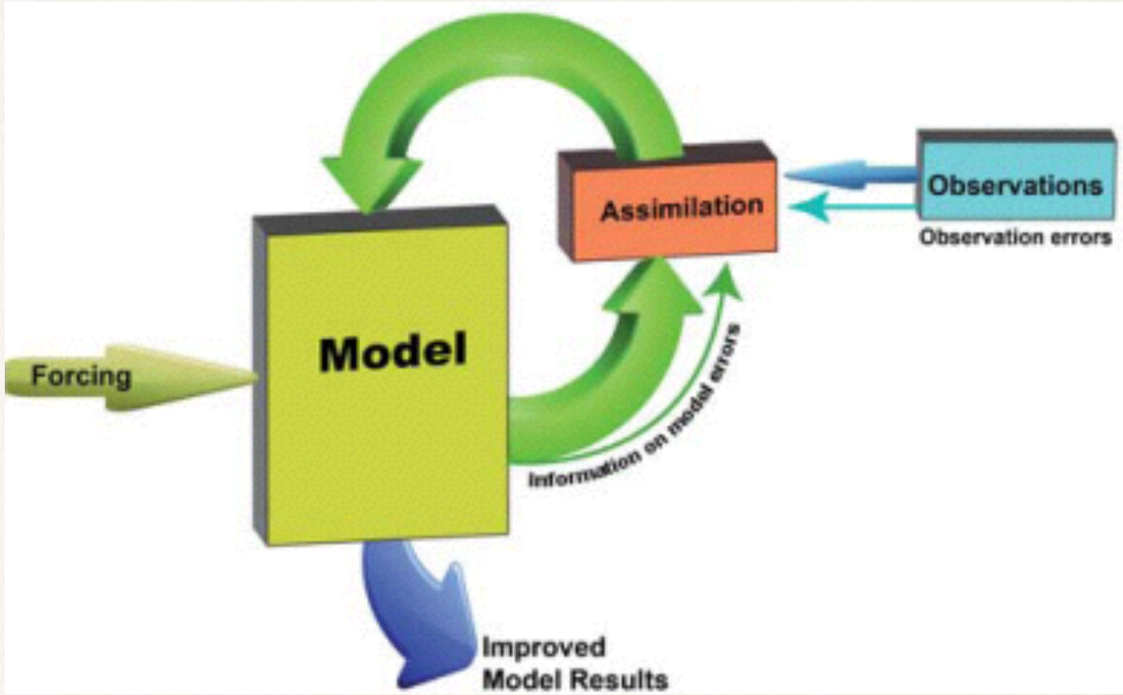
ollowing (σ)

e best choice for shallow coastal regions

Advances Ocean modelling

Data Assimilation

Essential for ocean prediction because
a) non-linearity of many ocean processes
b) errors in atmospheric forcing
c) models are imperfect



Data currently assimilated
a) Vertical profiles (XBT, CTD, profiling floats)
b) satellite measurements (SST, SSH)

Advances Ocean modelling

Data Assimilation

Produce (in principle) a dynamically consistent depiction of the ocean

BUT … have to have skilled non-assimilative model

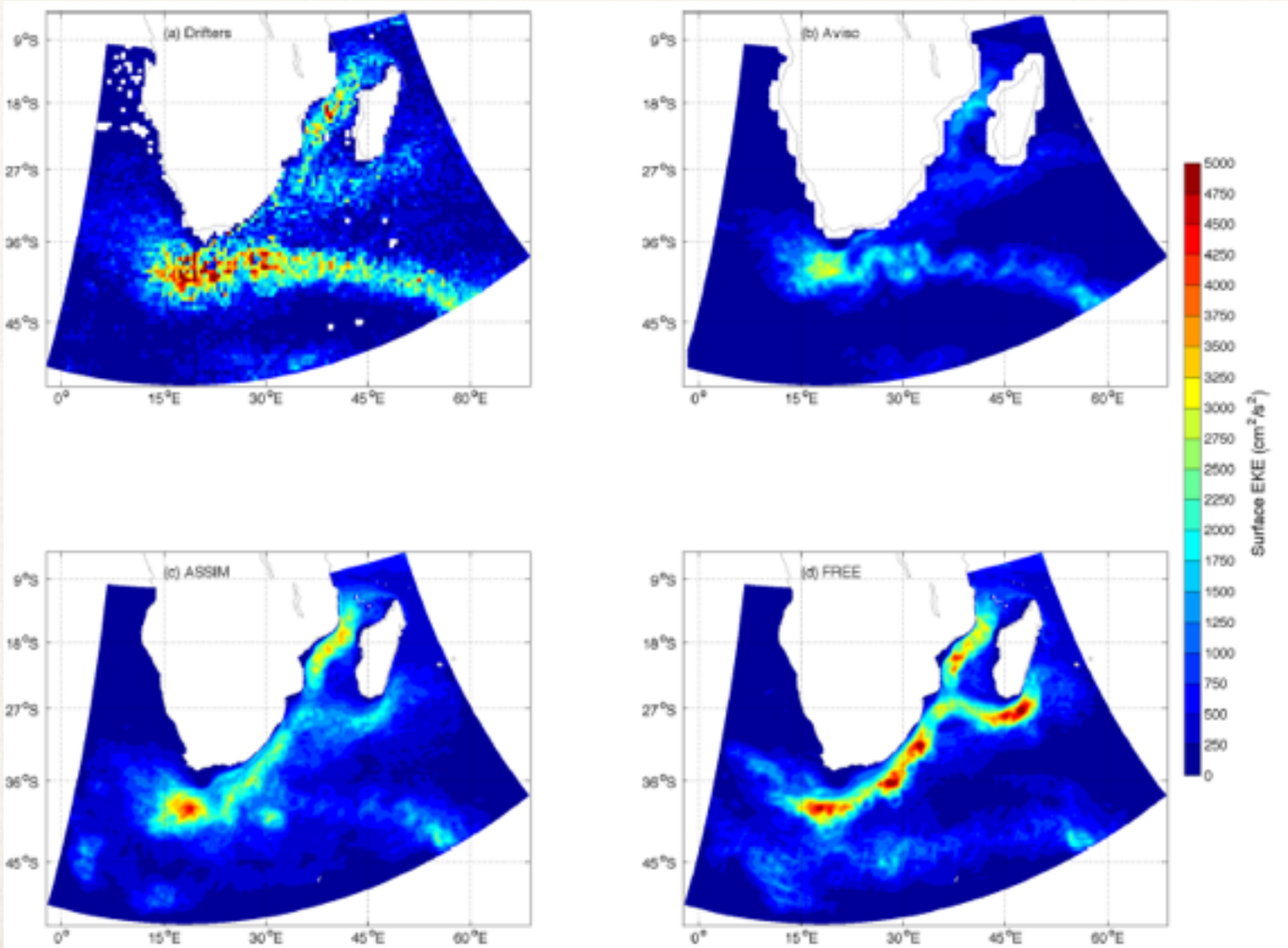


Fig. 5 Mean surface eddy kinetic energy (cm^2/s^2) derived from surface velocities of (**a**) the drifter data, (**b**) Aviso NRT persistence, (**c**) ASSIM and (**d**) FREE

Backeberg et al. 2014.

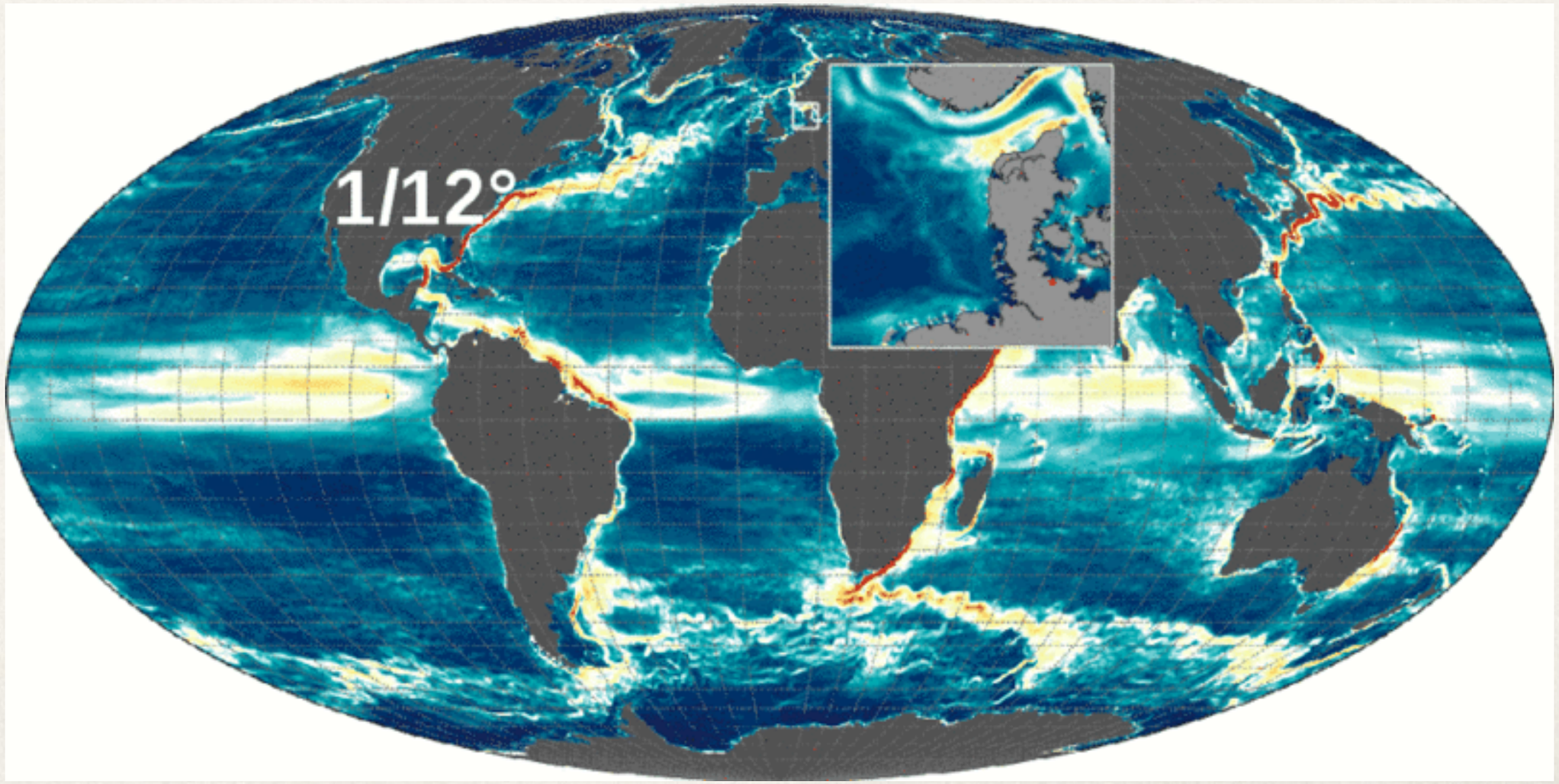
Global Ocean models

ORCA05, ORCA025, ORCA12

Global ocean hind cast at various resolutions

Investigate large-scale and mesoscale variability

Used as base model for grid refinement



Global Ocean models

ORCA05, ORCA025, ORCA12

Numerical model - NEMO

Variable horizontal resolution (50km~9km)

46 vertical levels (z-levels)

Forced CORE-II

Data assimilated: None

Time period: past 20-30 years

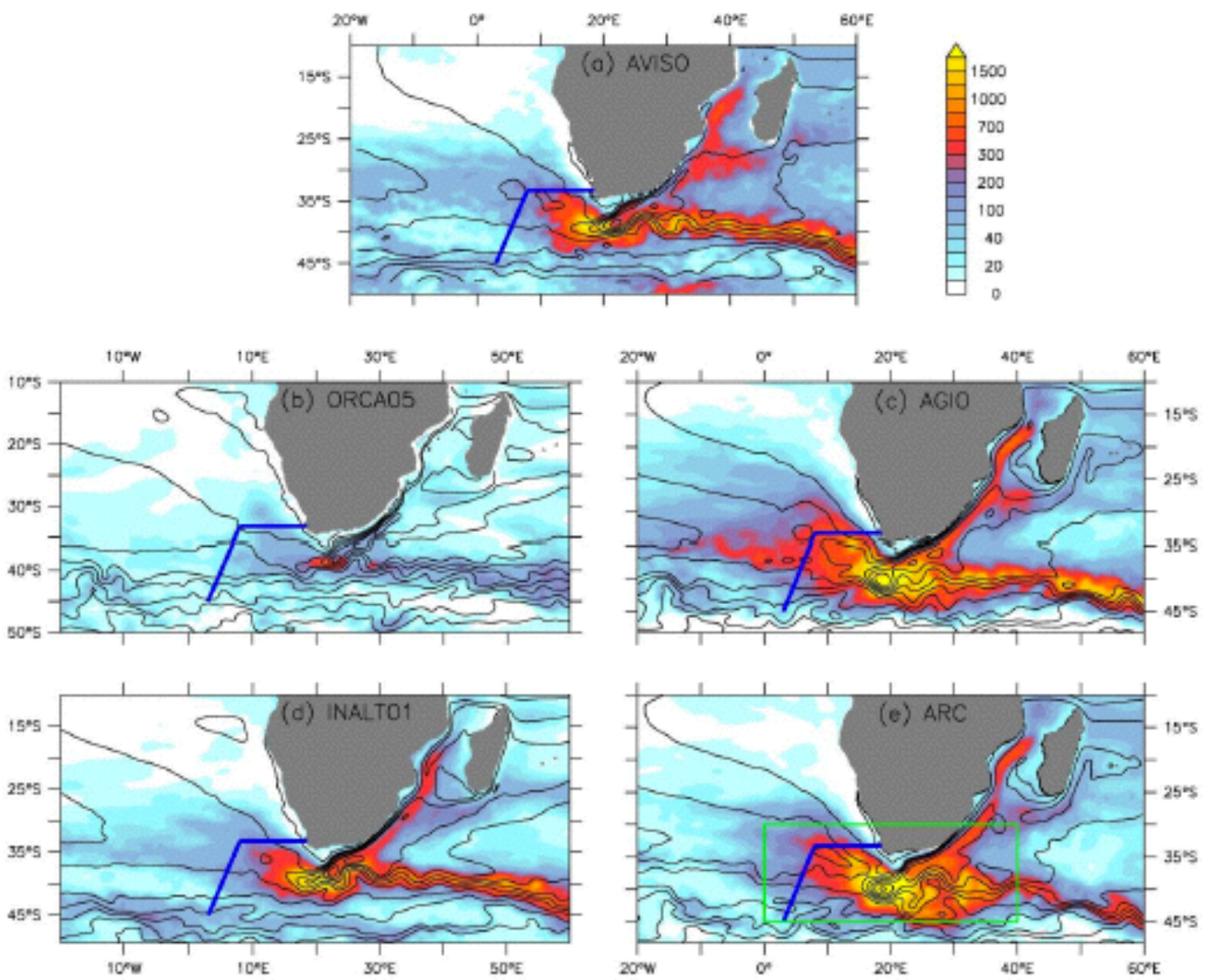


FIGURE 2.5: Representation of the mean circulation (contours of sea surface height (SSH) averaged for period 1992 – 2007, 20 cm contour interval) and mesoscale variability (shading of SSH variance, cm^2) of the Agulhas system from (a) altimetric observations, AVISO (http://aviso.oceanobs.com), (b) ORCA05, (c) AGIO, (d) INALT01 and (e) ARC (nested region, green box). Agulhas leakage is measured across the Good-Hope line (blue section). Adapted from Durgadoo et al. (2013).

Durgadoo, 2013. PhD thesis.

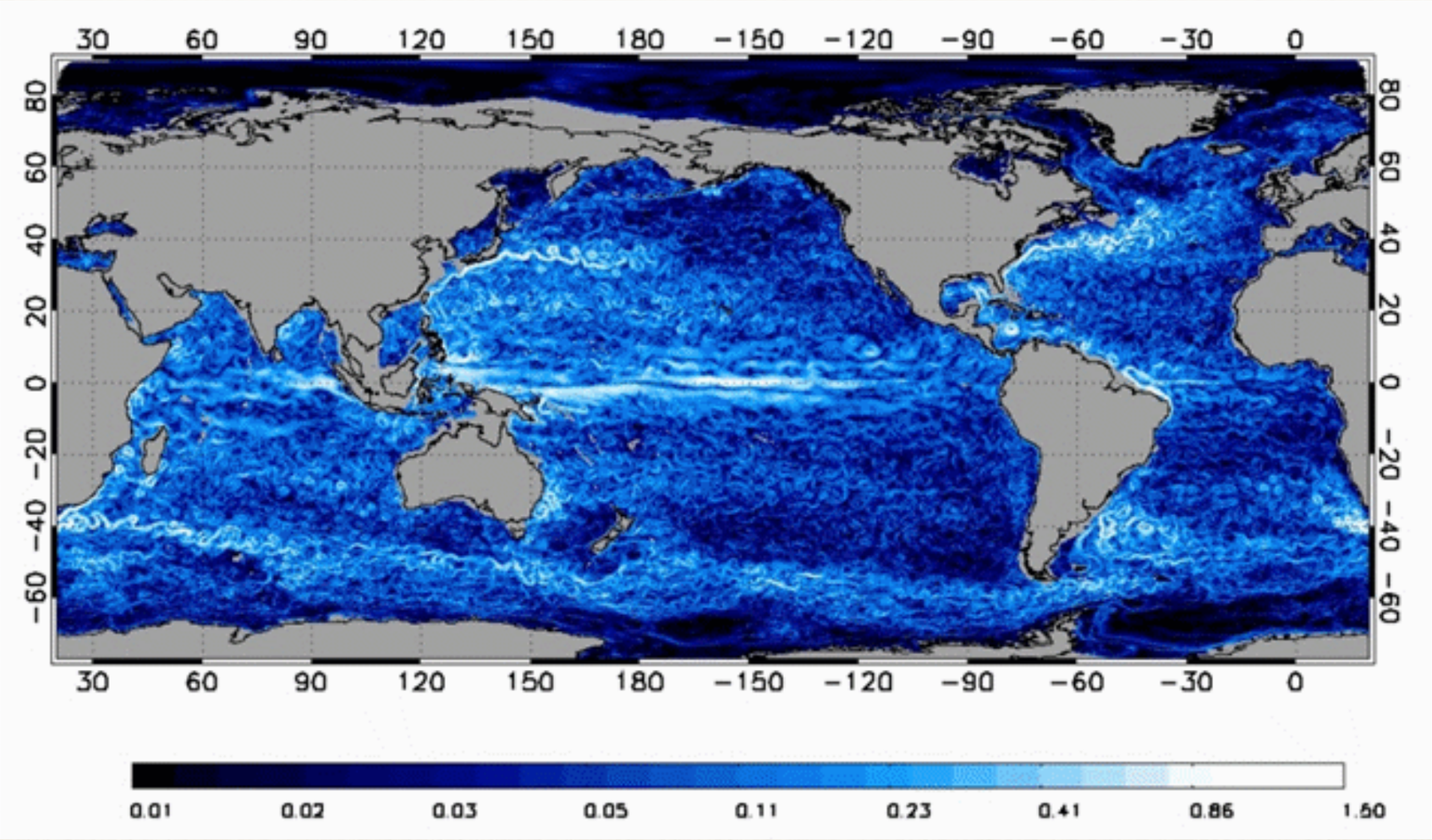
Global Ocean Reanalysis

GLORYS

assimilate historical observational data for improved accuracy

Eddy-permitting global ocean reanalysis product

Aim to describe the mean and time-varying state of the ocean circulation



Global reanalysed current speed (m/s) on 3 May 2003

Global Ocean Reanalysis

GLORYS

Numerical model - NEMO ORCA025 config

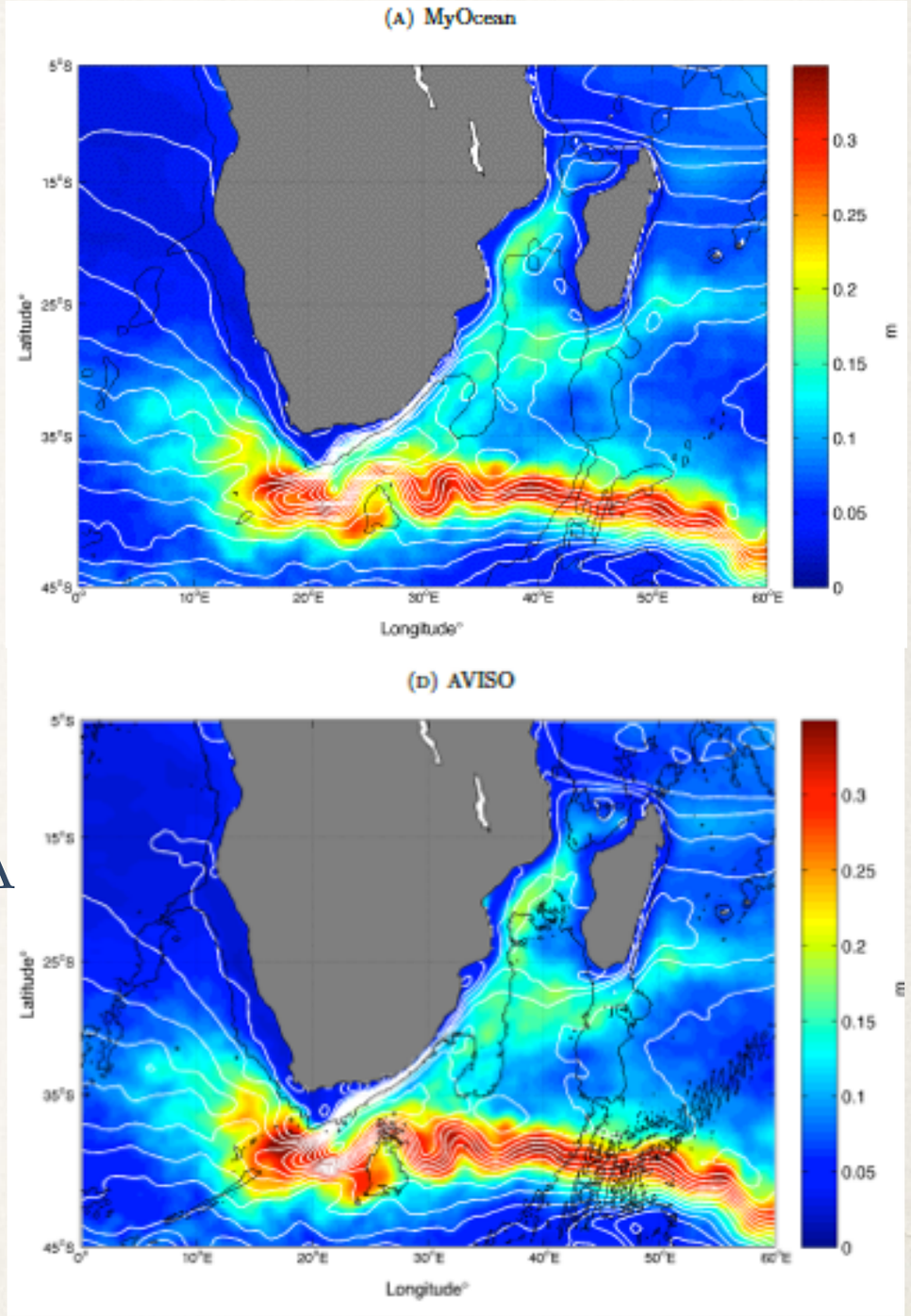
Horizontal resolution ~25km

75 vertical levels (z-levels)

Forced with ERA-interim

Data assimilated: SST, T/S profiles, along track SLA

Time period: 1993-2015



Mean SSH (white contours) and RMS (colour) for GLORYS and AVISO

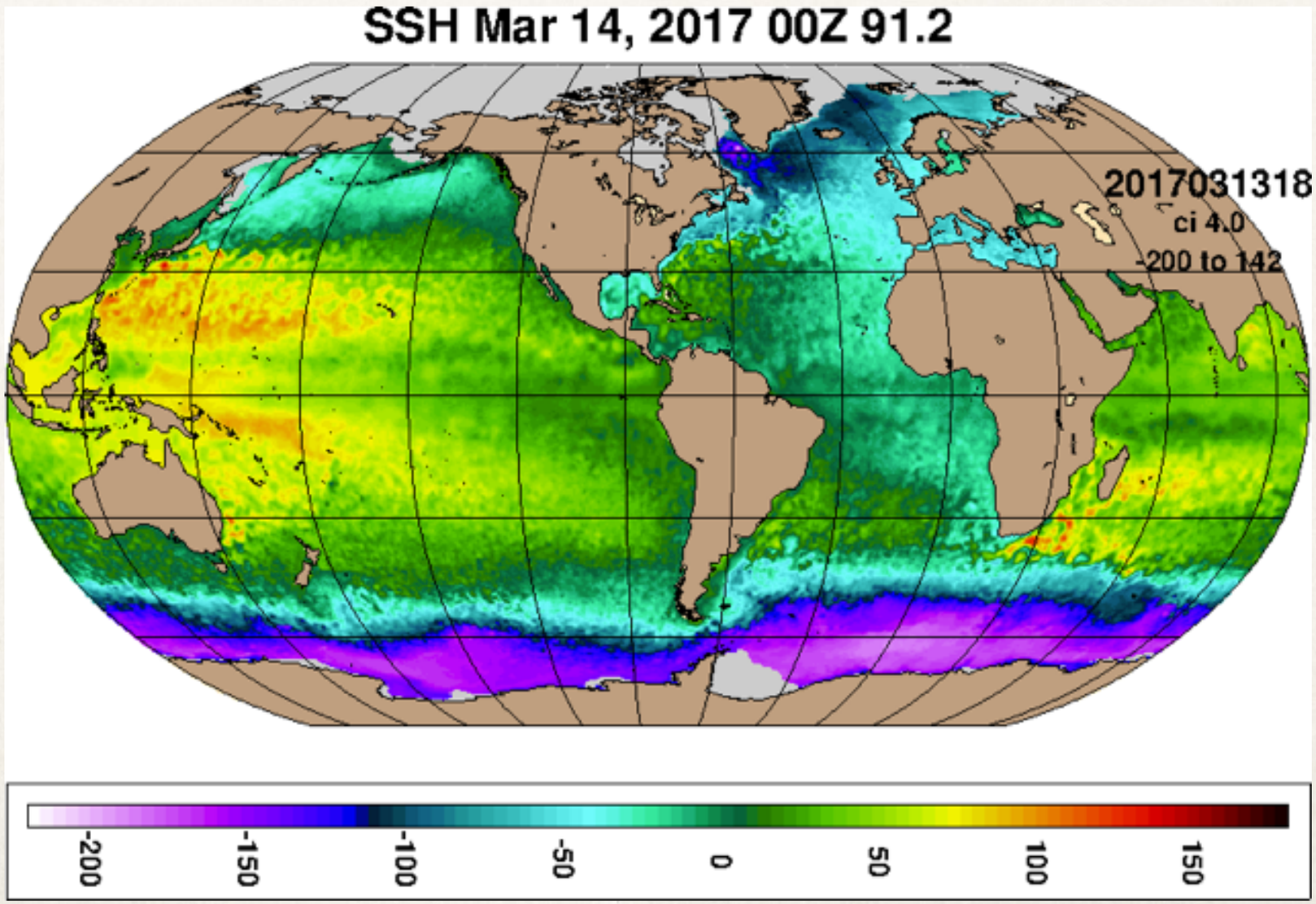
Cooper. 2014. MSc thesis.

Global Ocean Reanalysis

Global - Hybrid Coordinate Ocean Model (G-HYCOM)

Depict and predict the 3D global ocean state at fine resolution

Developed by the US Navy



Global Ocean Reanalysis

Global - Hybrid Coordinate Ocean Model (G-HYCOM)

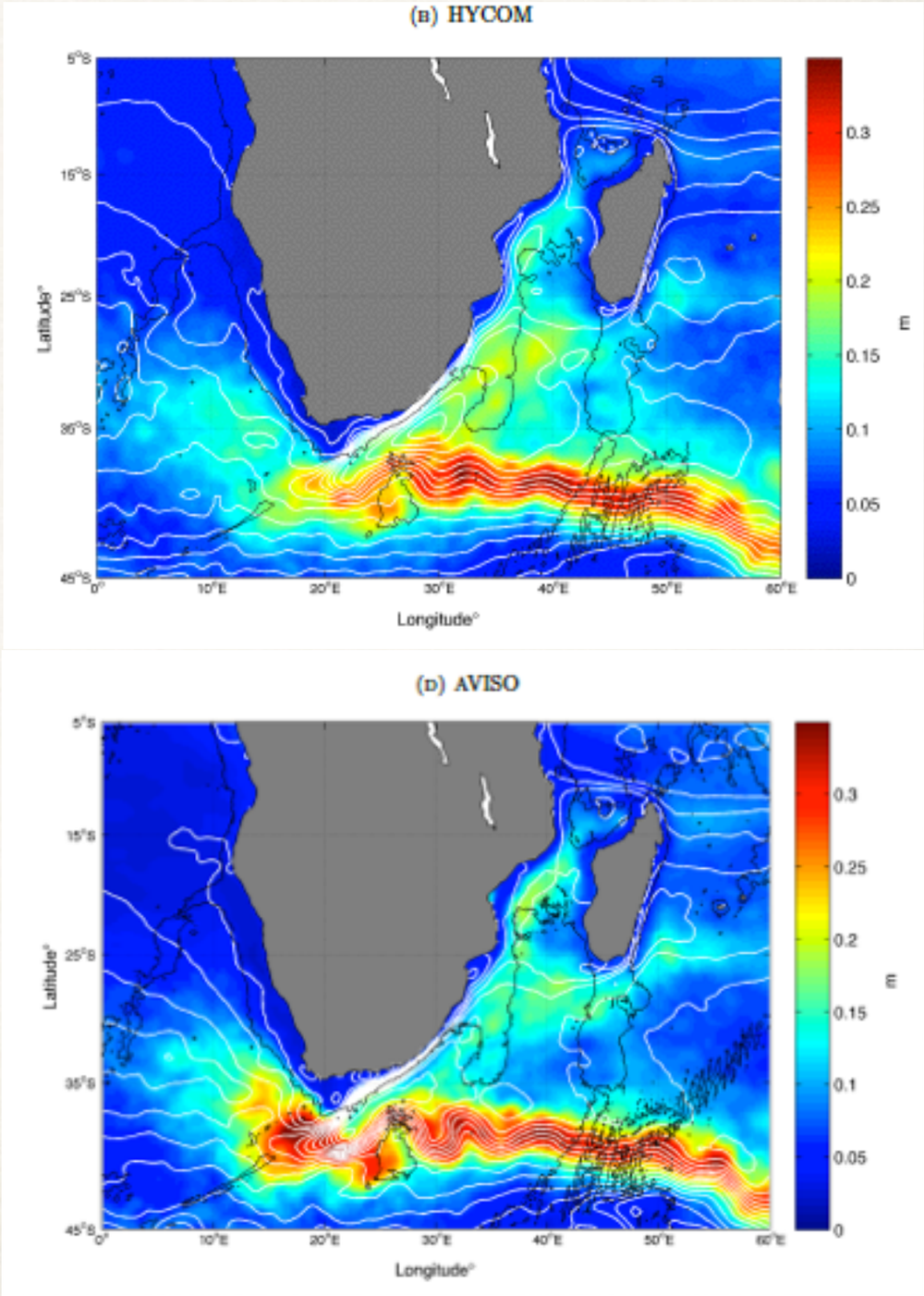
Numerical model - HYCOM

Horizontal resolution ~9km

40+ hybrid vertical levels

Forced with NOGAPS

Data assimilated: SSH, SST, XBT, CTD, Argo floats



Mean SSH (white contours) and RMS (colour) for G-HYCOM and AVISO

Cooper. 2014. MSc thesis.

Regional Ocean models

AGULHAS

Purpose: Mesoscale variability of Agulhas Current System

Numerical model - HYCOM

Horizontal resolution ~9-11km nested in 30-40km

30 hybrid vertical levels

Forced with ERA40 and ECMWF

Time span: 1996-2006

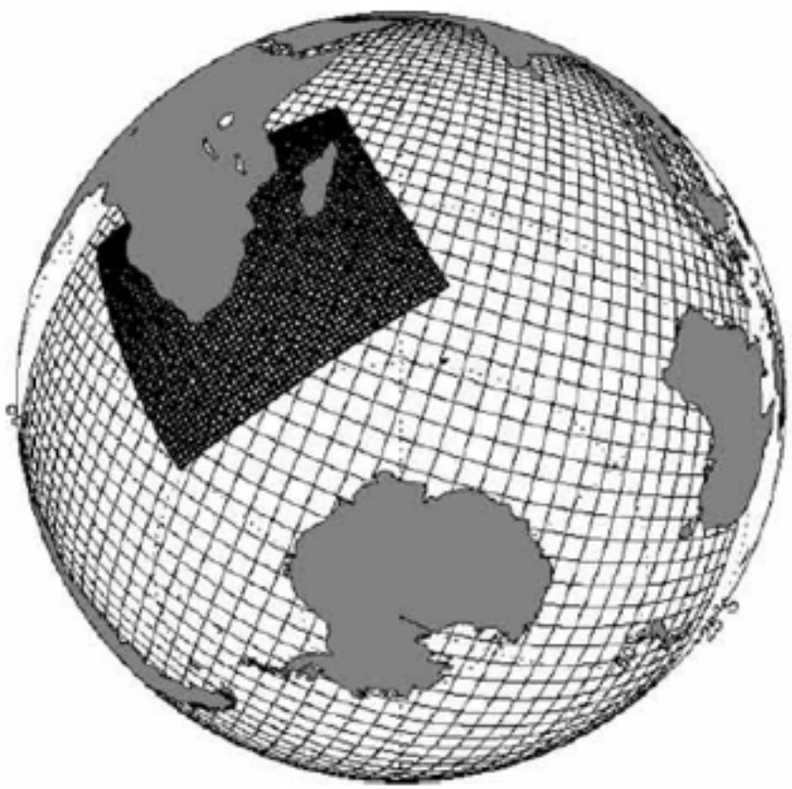


Fig 1: The HYCOM model system. Every tenth grid point was plotted to produce the respective mesh grids, therefore each box consists of 10x10 grid cells. The coarse mesh grid indicates the domain of the parent model grid and the fine mesh grid the nested high resolution Agulhas model

Regional Ocean models

AGULHAS

Improvements: Improved numerics through 4th order advection scheme

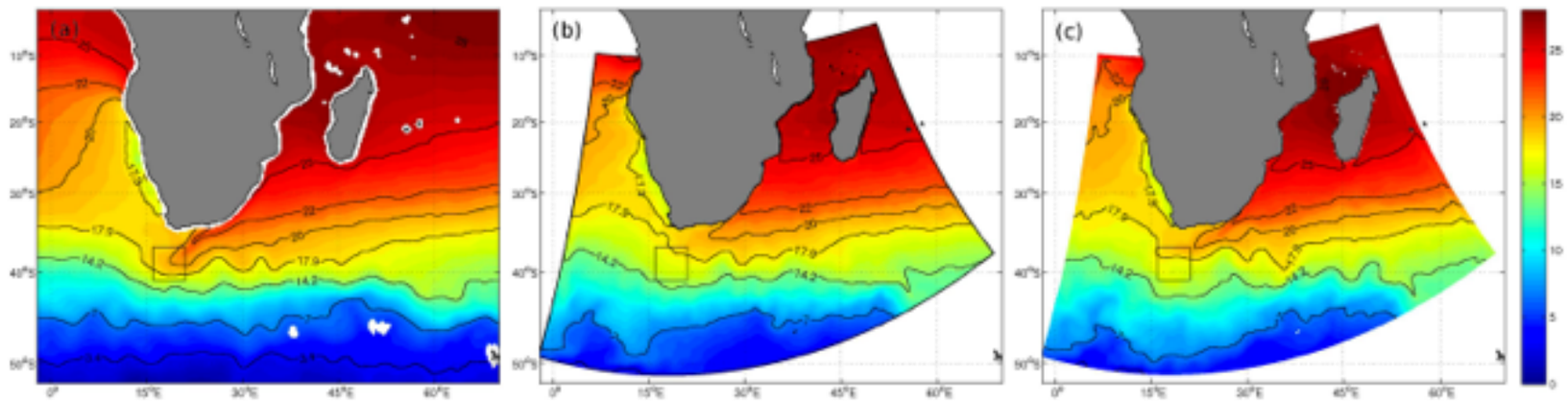


Fig. 4. Mean sea surface temperatures (SSTs, °C) for the period 2004–2006 from MW SST (**a**), HYCOM O2 (**b**) and HYCOM O4 (**c**).

Assimilation of along-track SLA

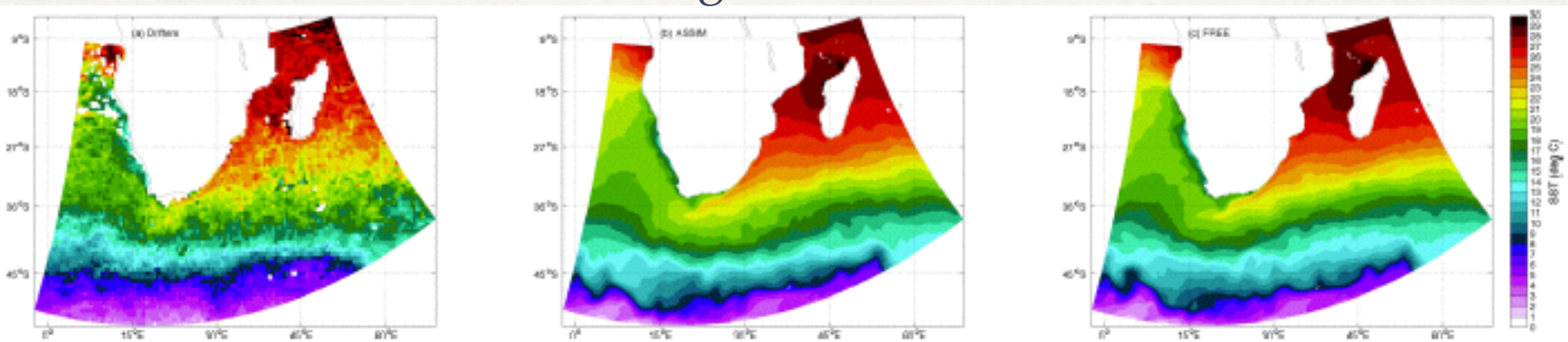


Fig. 6 Mean sea surface temperatures (°C) from **a** the drifter data, **b** ASSIM and **c** FREE

Backeberg et al. 2009, 2014.

Regional Ocean models

Southern Africa Experiment (SAfE)

Purpose: Regional model that resolves the major oceanic phenomena around Southern Africa

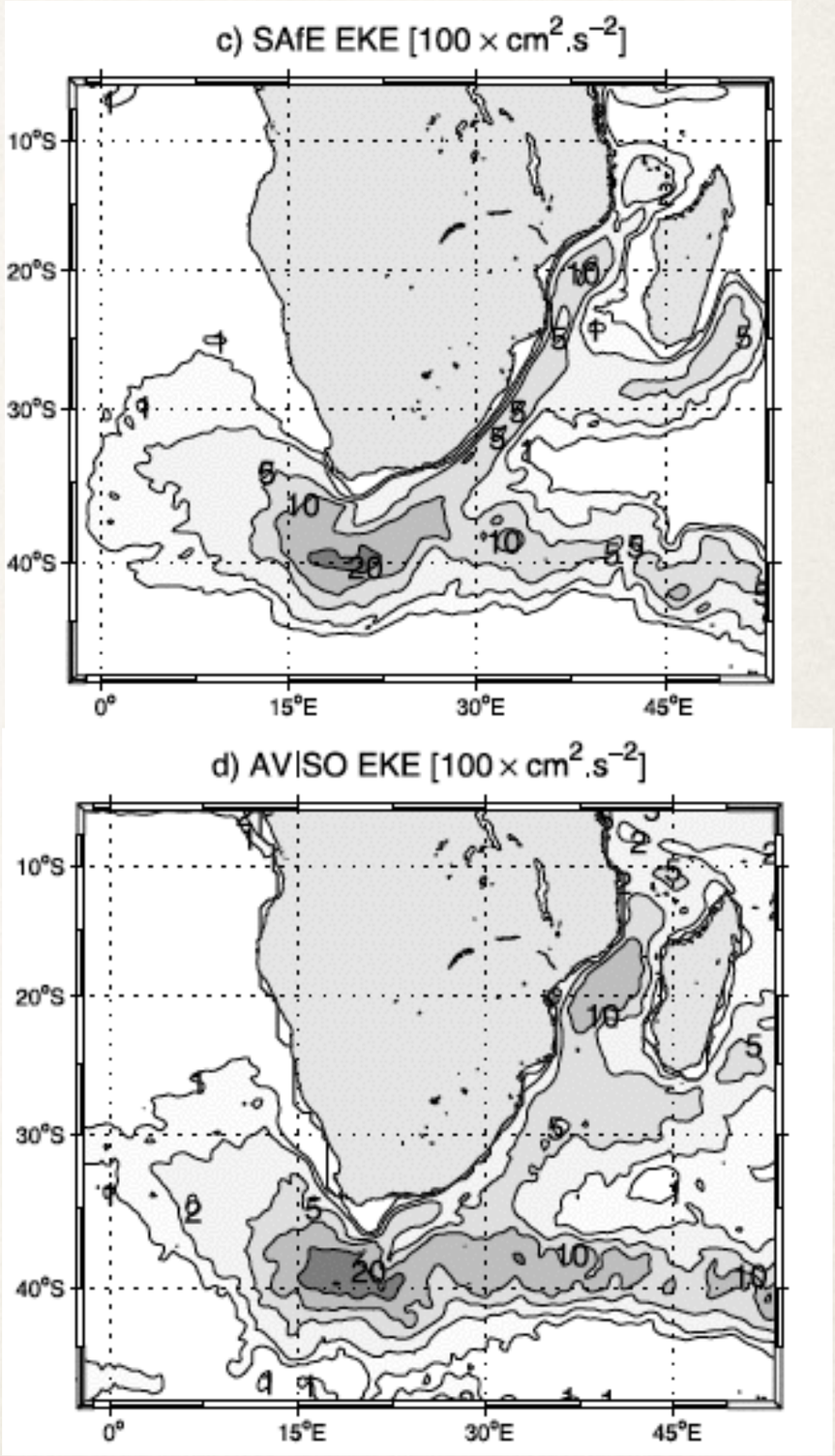
<u>Original Configuration</u>

Numerical model - ROMS

Horizontal resolution ~20-25km

32 terrain-following vertical levels

Forced with NCEP reanalysis



SAfE and Aviso Mean EKE

Penven et al. 2006. *GRL*

Regional Ocean models

Southern Africa Experiment (SAfE)

This configuration has been adapted (and extended) over the years for various purposes

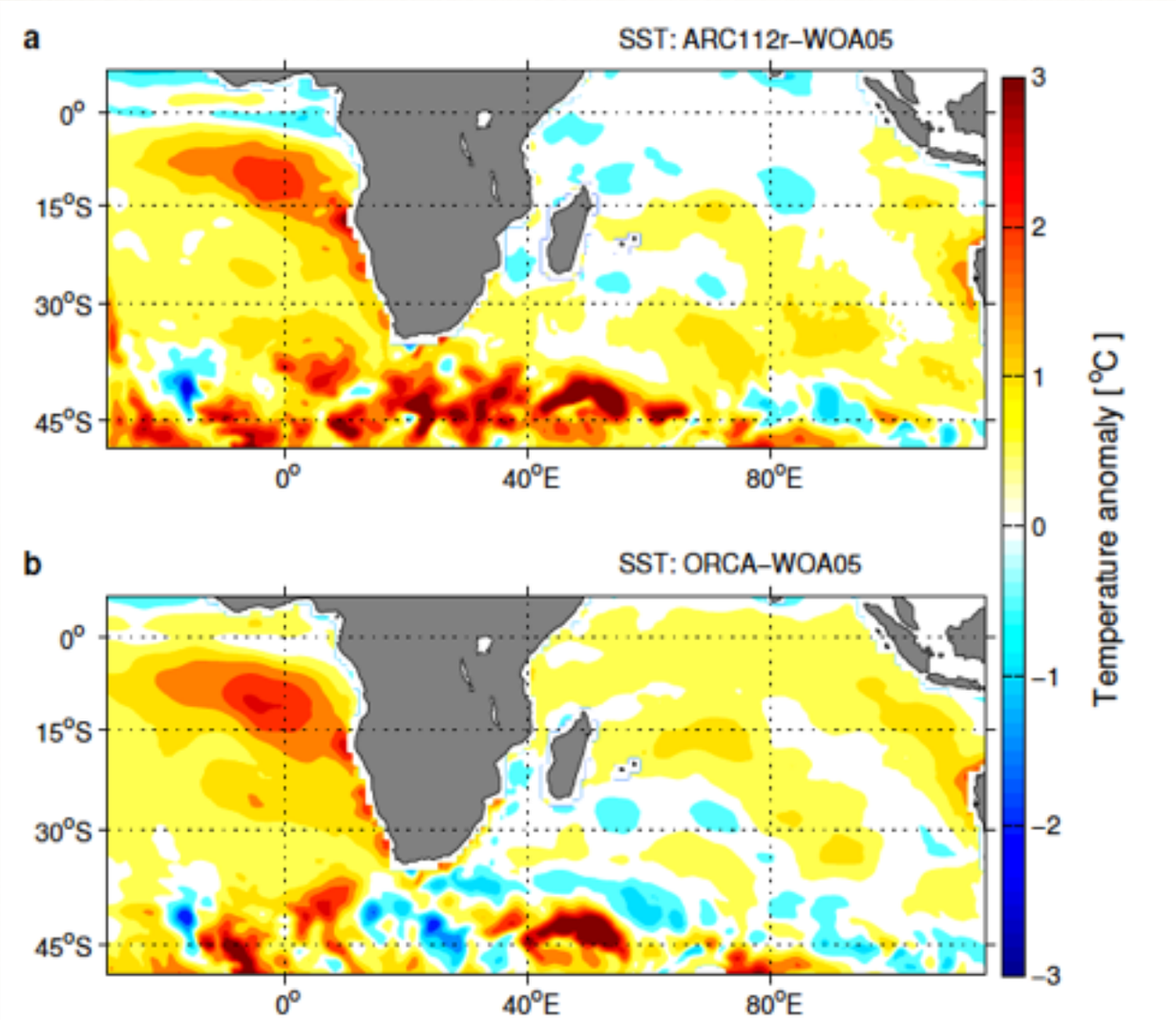


Figure 3.2: Climatological a) ARC112r and b) ORCA05 sea-surface temperature (SST) anomalies from WOA05 fields.

<u>AGIO</u>

Horizontal resolution ~25 km

32 terrain-following vertical levels

Forced with CORE-II

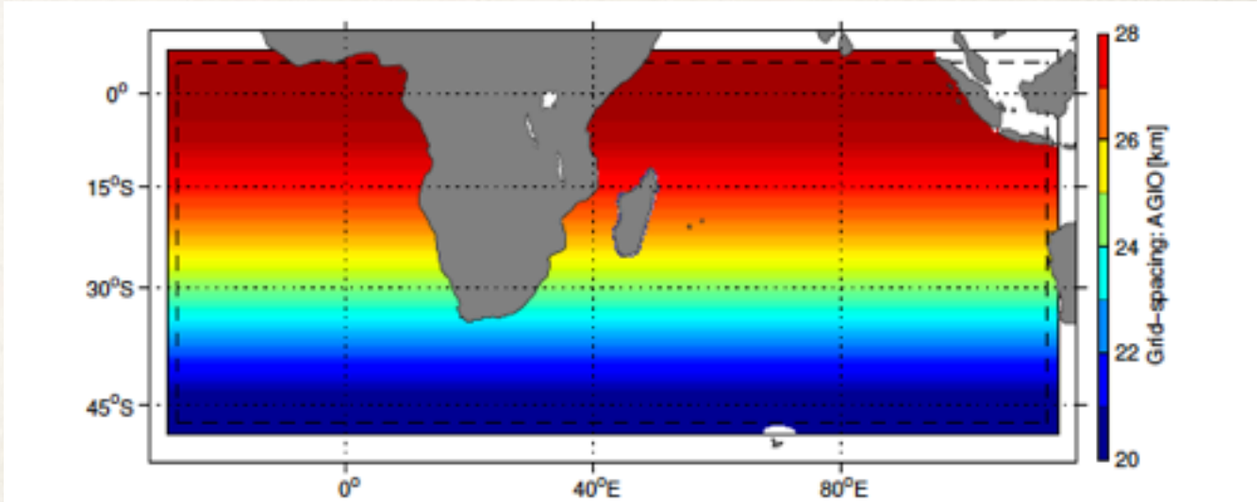


Figure 2.5: The extent and resolution of the AGIO domain at 1/4° resolution. The solid line shows the domain extent. The dashed line shows the extent of the sponge layer. White areas in the Indonesian Archipelago and around Kerguelin Island indicate masking. The average resolution over the greater Agulhas region is ∼23 km.

Loveday, 2014. PhD thesis.

Regional Ocean models

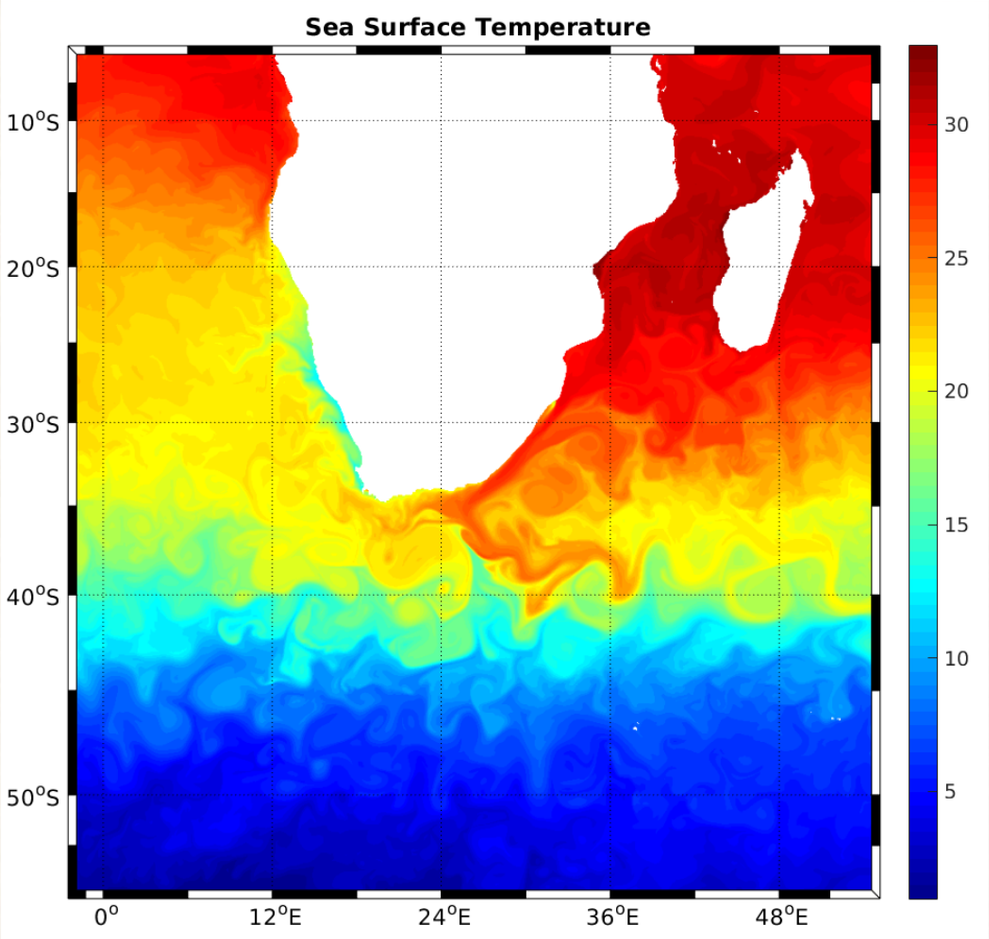
Southern Africa Experiment (SAfE)

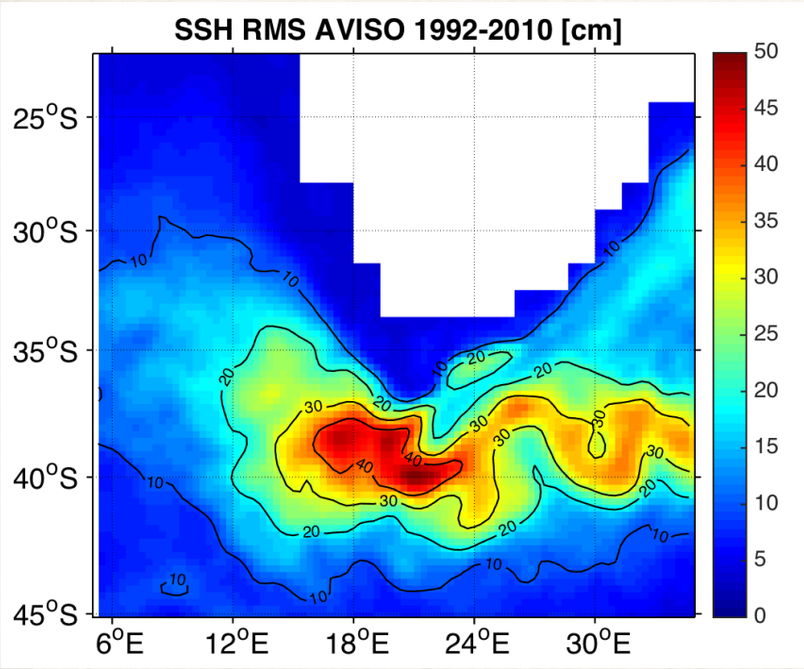
BENG-SAFE15
Horizontal resolution ~7.5 km

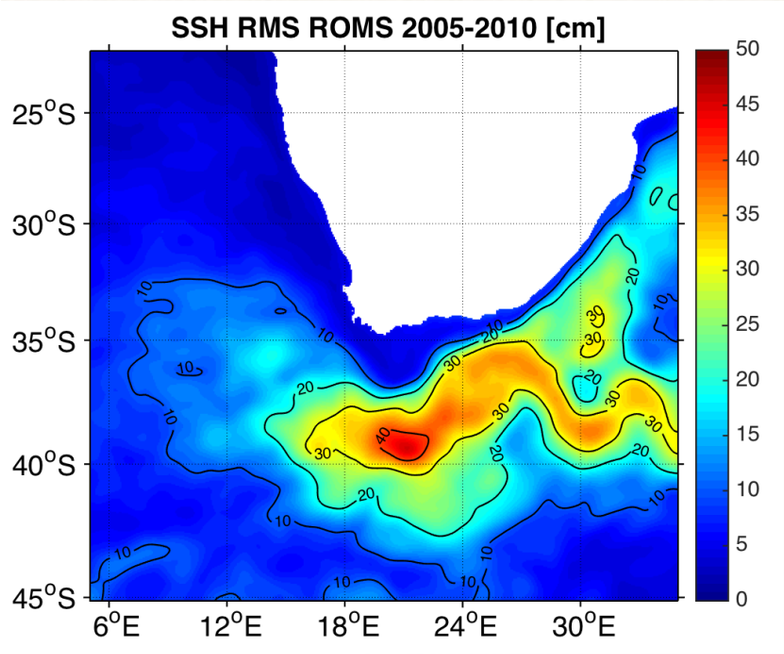
100 terrain-following vertical levels

Forced with CFSR

Time span: 1992-2010







Accuracy of ocean models

Accuracy depend on

Resolution - higher resolution resolves more small scale processes

Numerics - more advanced numerics lead to more accurate representation

Data quality - biases in forcing and boundary data will be transferred to model

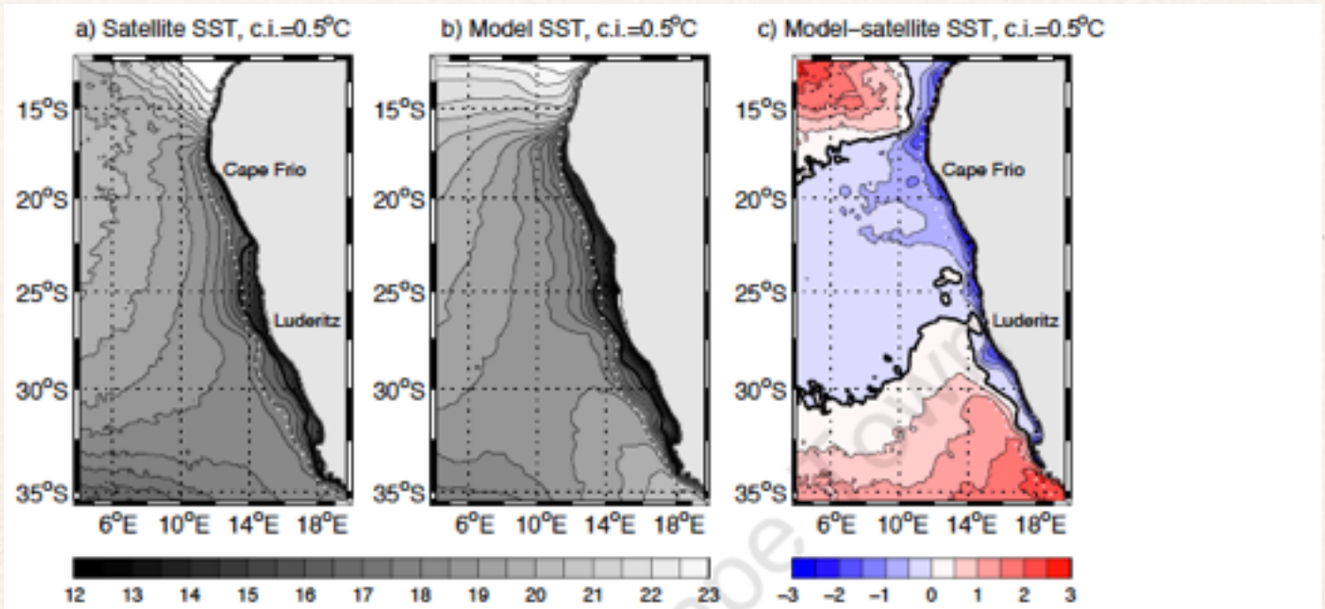


Figure 4.2: Annual mean satellite (a) and model (b) SSTs in the Benguela system. The dotted white line represents the approximate position of the shelf-edge. The difference between satellite and model SSTs (model - satellite) are shown in (c). Positive (negative) values indicate an over-estimation (under-estimation) of SSTs by the model.

Veitch. 2009. PhD thesis.

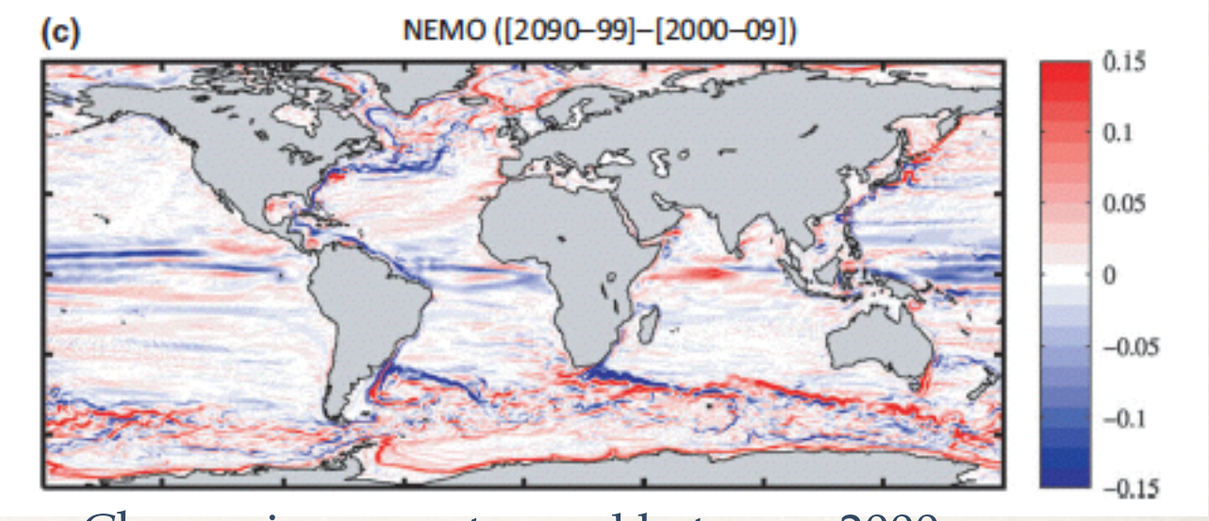
Ocean models and climate change

Global changes in ocean circulation

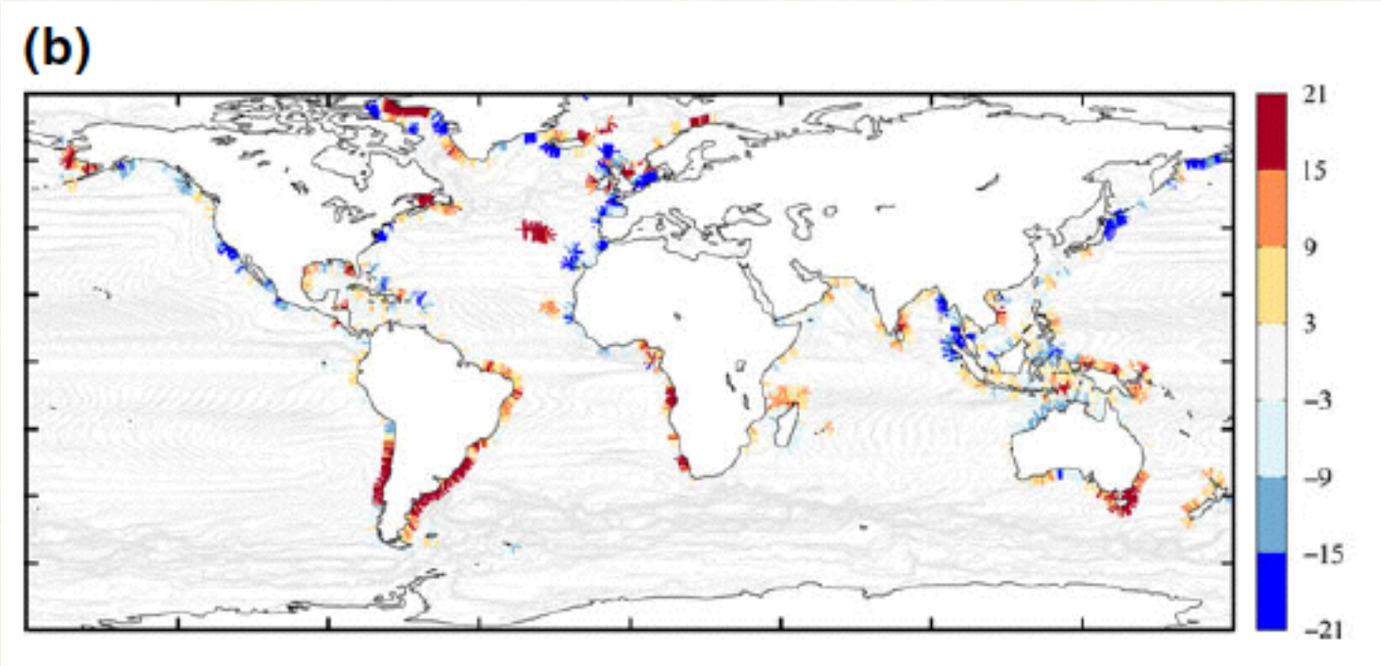
<u>Model Configuration</u>
Numerical model - NEMO

Horizontal resolution ~20-25km

Simulation period 1977-2099 under strong warming



Change in current speed between 2000s and 2090s. Red (blue) indicates stronger (weaker) currents under strong warming.



Predominant poleward displacement of particles (indicated in red) in southern hemisphere under strong warming.

Gennip et al. 2017. *Global Change Biology*

Conclusion

Hydrodynamic models

The last decade has seen significant progress in ocean modelling

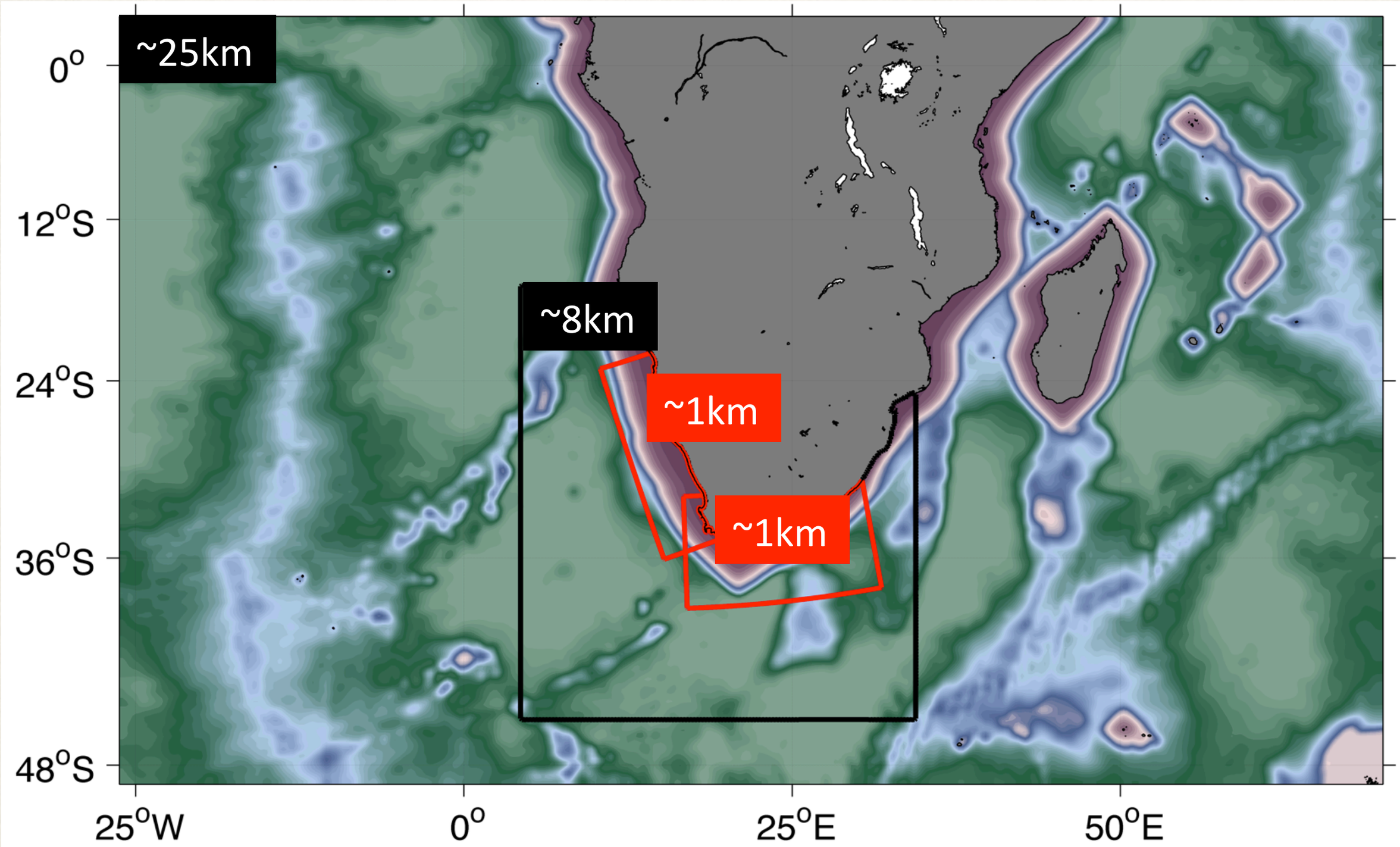
- Resolution (horizontal and vertical)
- Numerics
- Data assimilation

… progress towards high-resolution reanalysis and predictive systems

… progress towards coupled systems (atmosphere-physics-biogeochemistry)

Hydrodynamic models for climate change

due to prevailing limitations the use of hydrodynamic models for climate change impact studies have been limited.

BUT …

Coastal-Orientated Regional Ocean Model of Southern Africa (COROMOSA)