Met Office

Across the ‘grey zone’ of ocean resolutions

Helene Hewitt

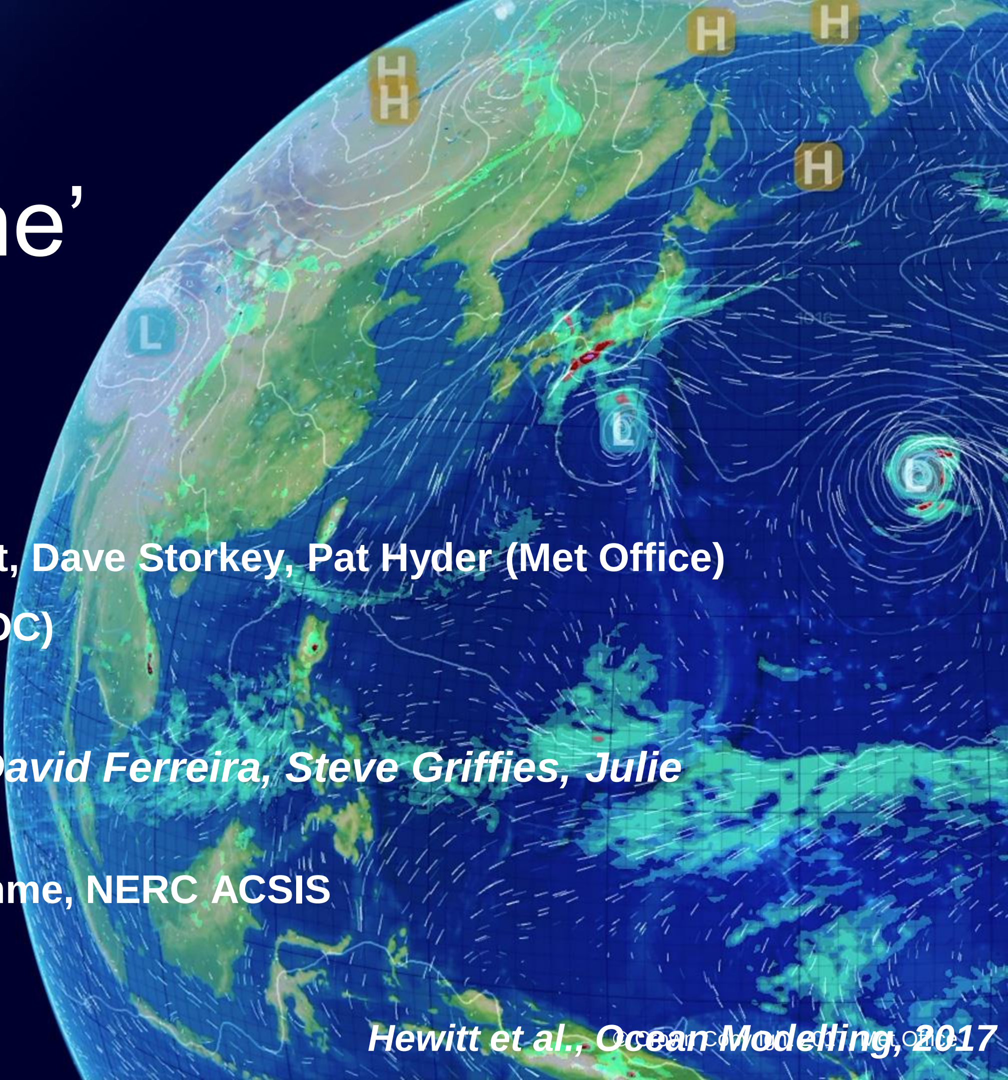
Malcolm Roberts, Pierre Mathiot, Daley Calvert, Dave Storkey, Pat Hyder (Met Office)

Andrew Coward, Bablu Sinha, Joel Hirschi (NOC)

Sophia Ashby (University of Reading)

Mike Bell, Eric Chassignet, Arnaud Czaja, David Ferreira, Steve Griffies, Julie McLean, Adrian New

EU Primavera, Hadley Centre Climate Programme, NERC ACSIS



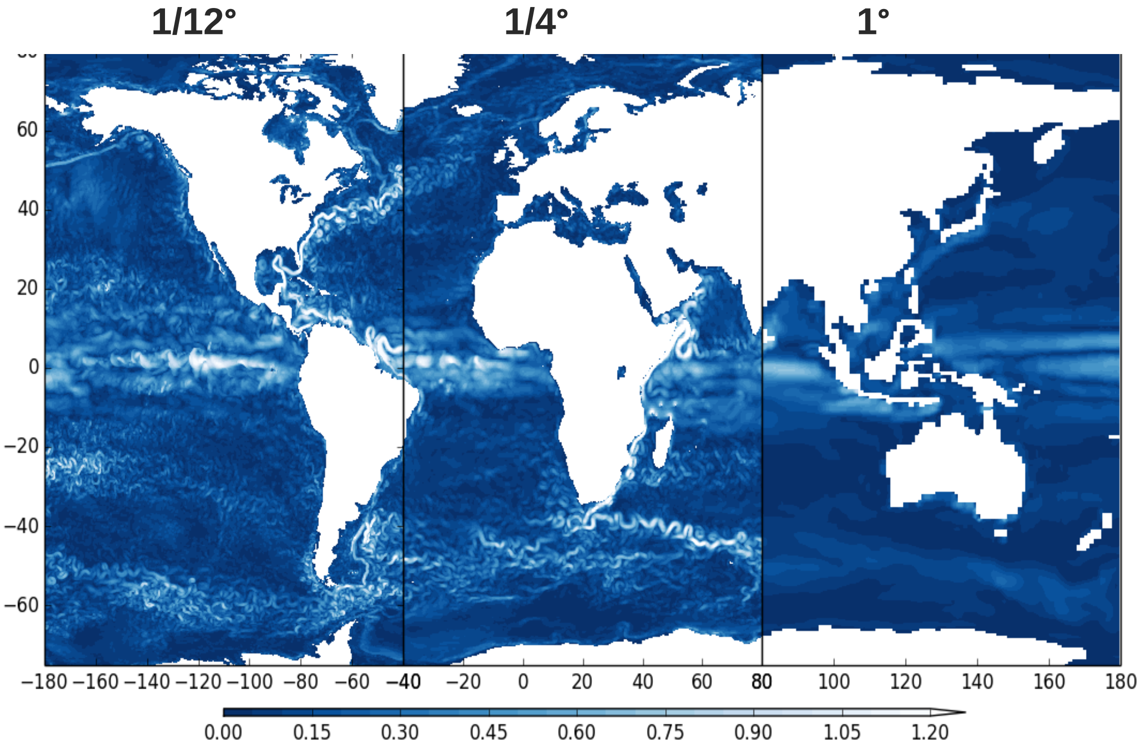
helene.hewitt@metoffice.gov.uk

@ht_hewitt

Hewitt et al., Ocean Modelling, 2017

Outline

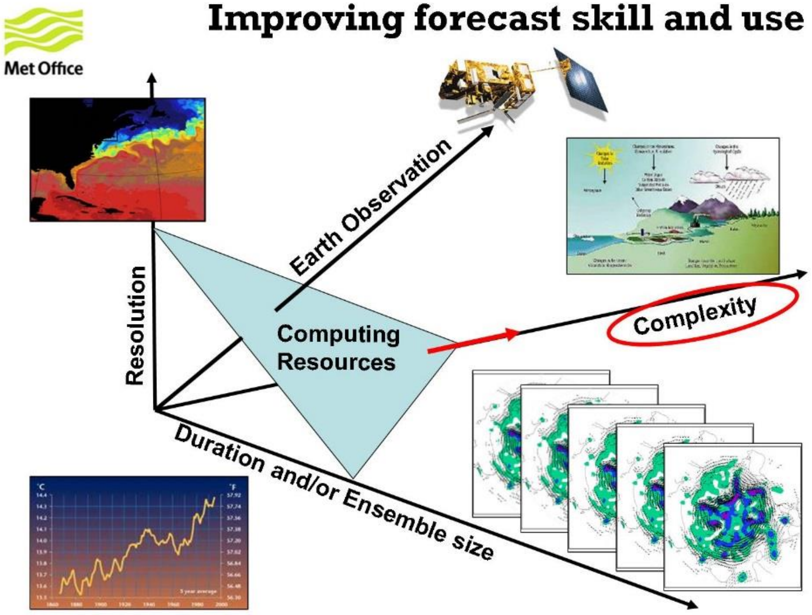
1. Introduction
2. Horizontal resolution in (global) ocean forced models
3. Traceable hierarchies and parameterisation
4. Sensitivity to resolution in coupled systems
5. Vertical resolution
6. Summary

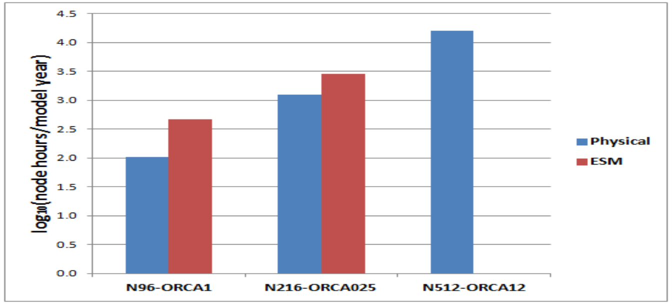


See Hewitt et al. (2017) review in Ocean Modelling

1. Introduction

- Scientifically, resolution should be chosen based on the scales that can be resolved
- However, the choice of resolution is usually made on the basis of computational constraints
- Shorter range predictions can run with higher resolution models – climate models are very constrained in the choices





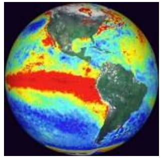
Global Physical Modelling

Unified Prediction across Timescales

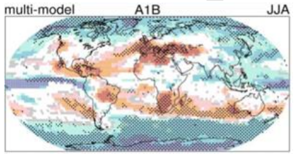
Hours | Days | Weeks | Months | Seasons | Decades | Centuries

1/12°

1/4°



1°



NWP - Atmosphere, Ocean, Waves

Deterministic   MOGREPS

GloSea   Decadal

Climate Change & UKESM1

Component Models	**Coupled AOIL Model**
GA7 , GL7, GO6, GSI7/8	GC3.0

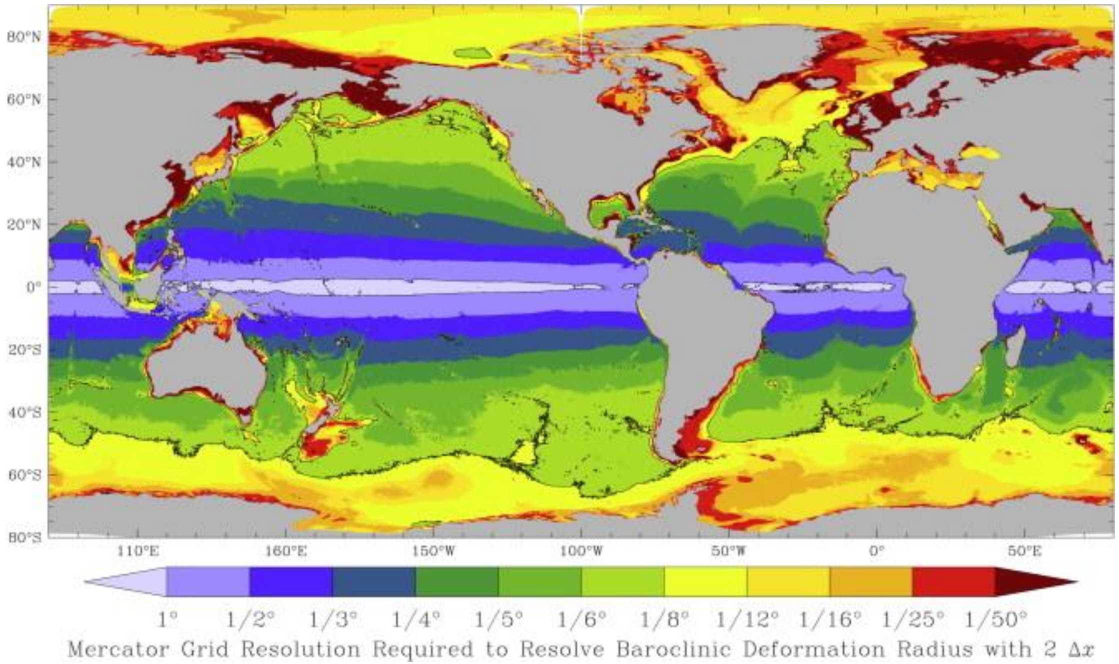
Met Office

Resolving the Rossby radius

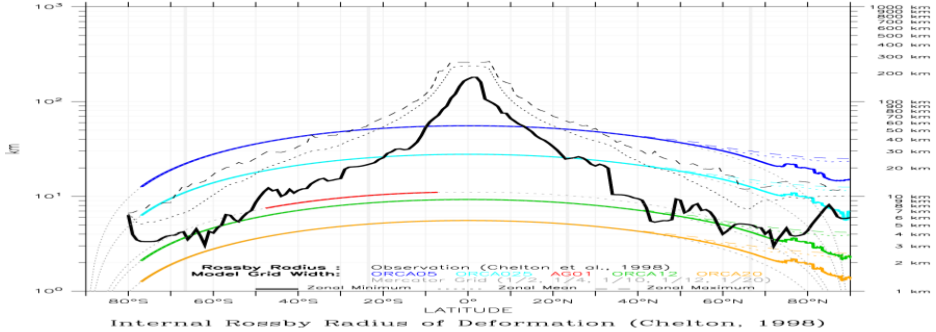
Rossby radius:

$$\frac{NH}{f}$$

N=Brunt-Vasaila frequency
H=depth
F=Coriolis parameter



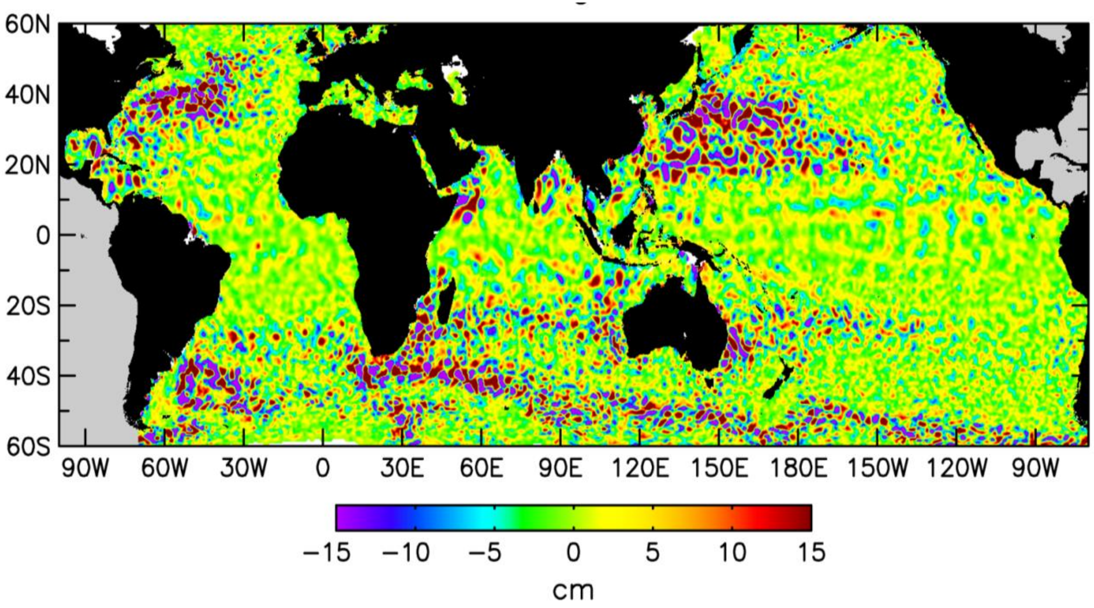
Hallberg 2013



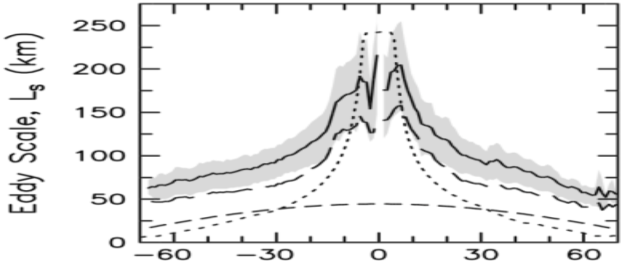
Markus Scheinert, Drakkar 2012

Observations of mesoscale eddies

- Coherent vortices, radius of about 50-100 km
- Generated by baroclinic and barotropic instabilities
- ~215,000 eddies with 4 weeks or longer lifetime over 20 years (Chelton et al., 2011)
- They are everywhere in the ocean!



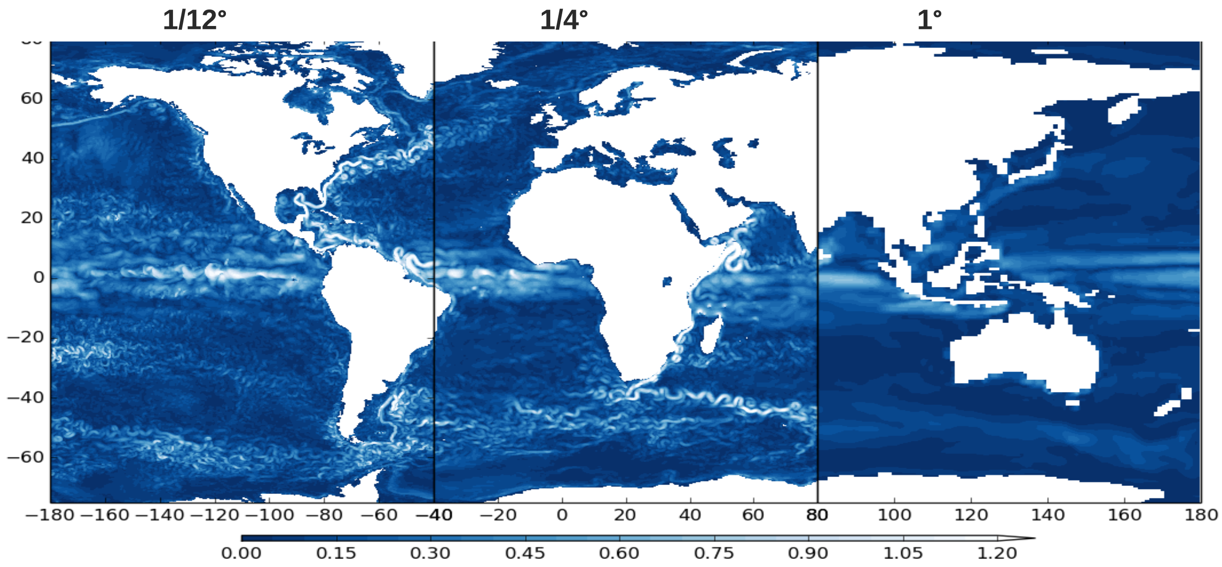
Chelton et al., 2011



Met Office

Spanning the eddy regime

- Across resolution the approach to parameterizing eddies changes
- Discuss Gent-McWilliams (GM) scheme for parameterizing eddies
- Note the existence of a grey zone



Eddy resolving

No GM, low isopycnal mixing

Eddy permitting

How to parameterise?

GM? Isopycnal mixing?

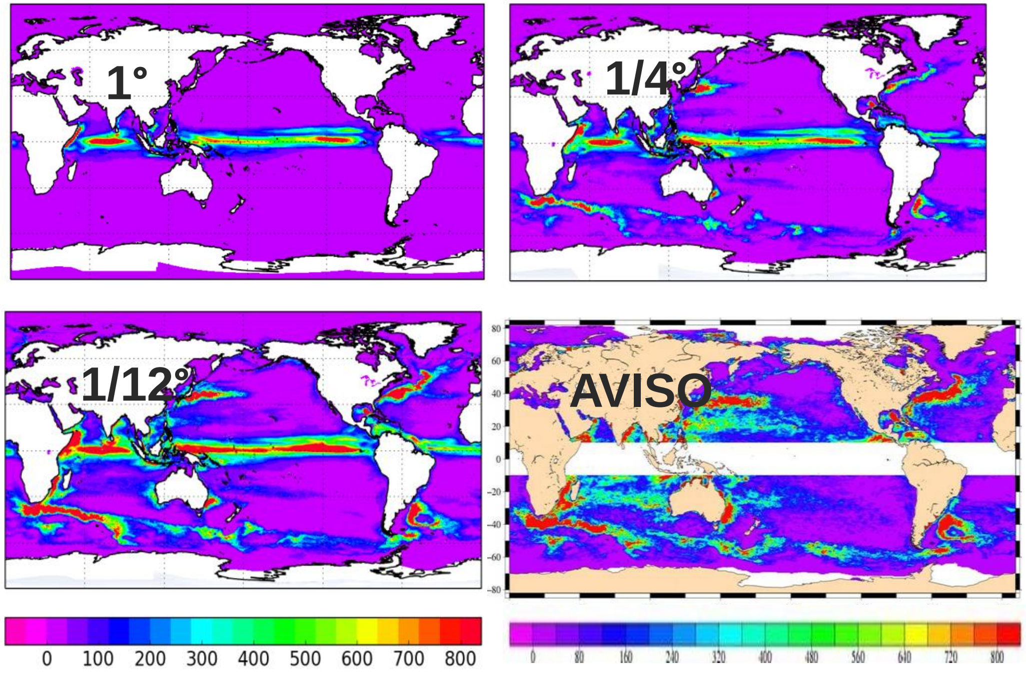
Scale selective?

Eddy parameterising

GM and isopycnal mixing

2. Horizontal resolution in forced ocean models

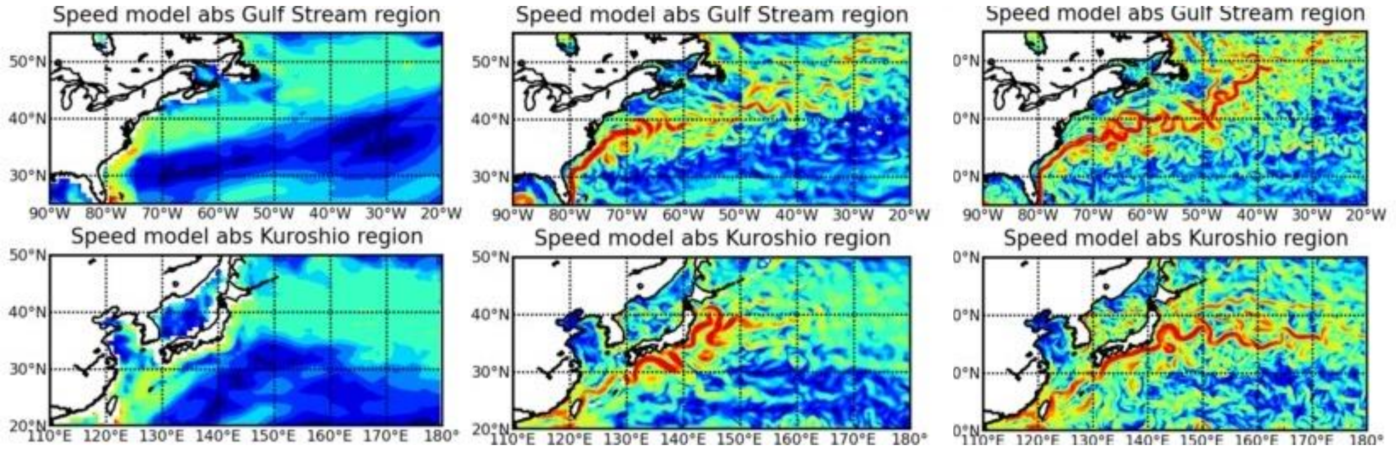
- Boundary currents and fronts
- Topographic control
- Impact of eddies and their parameterisation



Pierre Mathiot

Boundary currents and fronts

1°	1/4°	1/12°

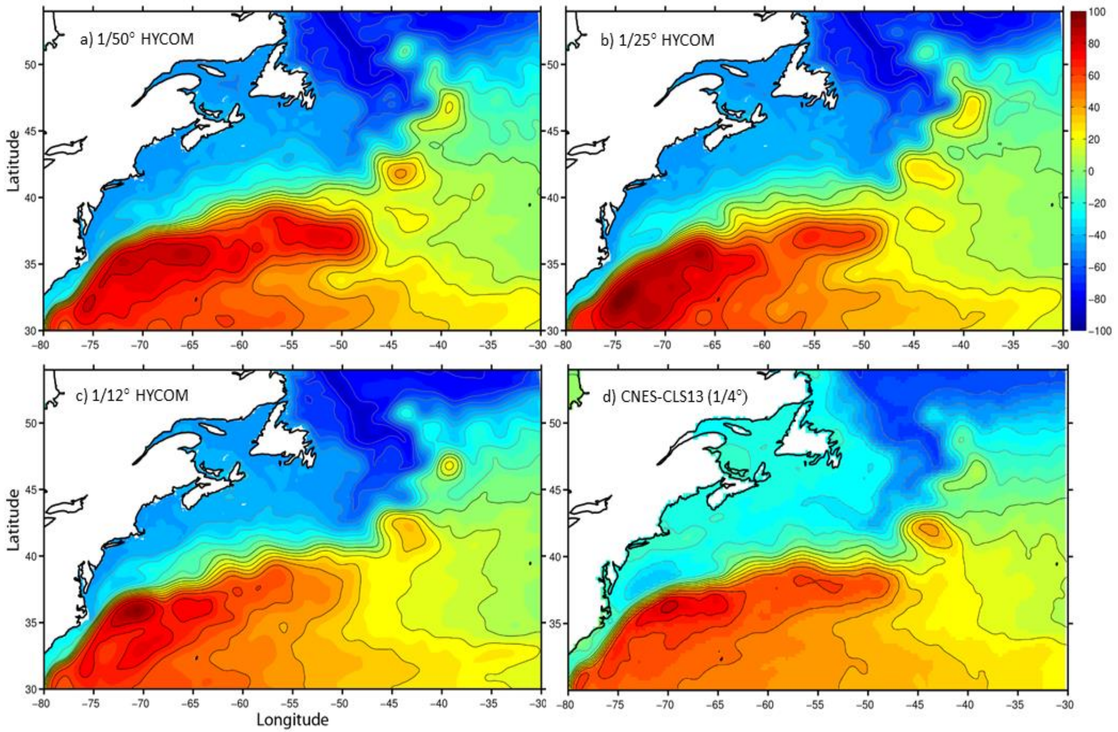


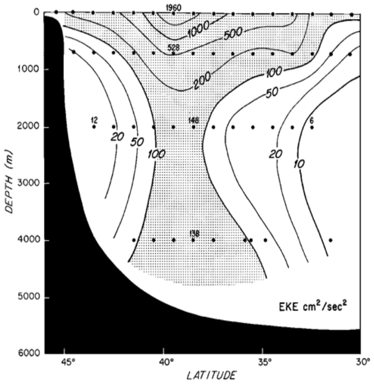
Move from diffusive regime to inertial regime as resolution increases

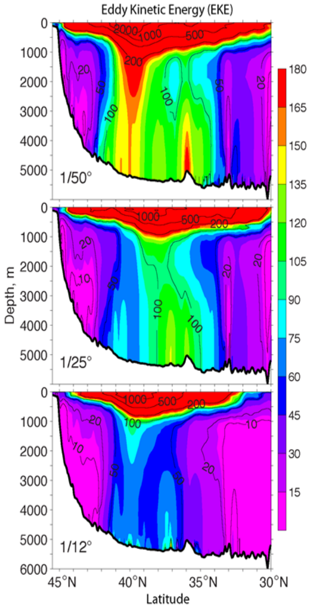
Both separation and penetration varies as resolution increases

Pat Hyder

Impacts beyond 1/12º



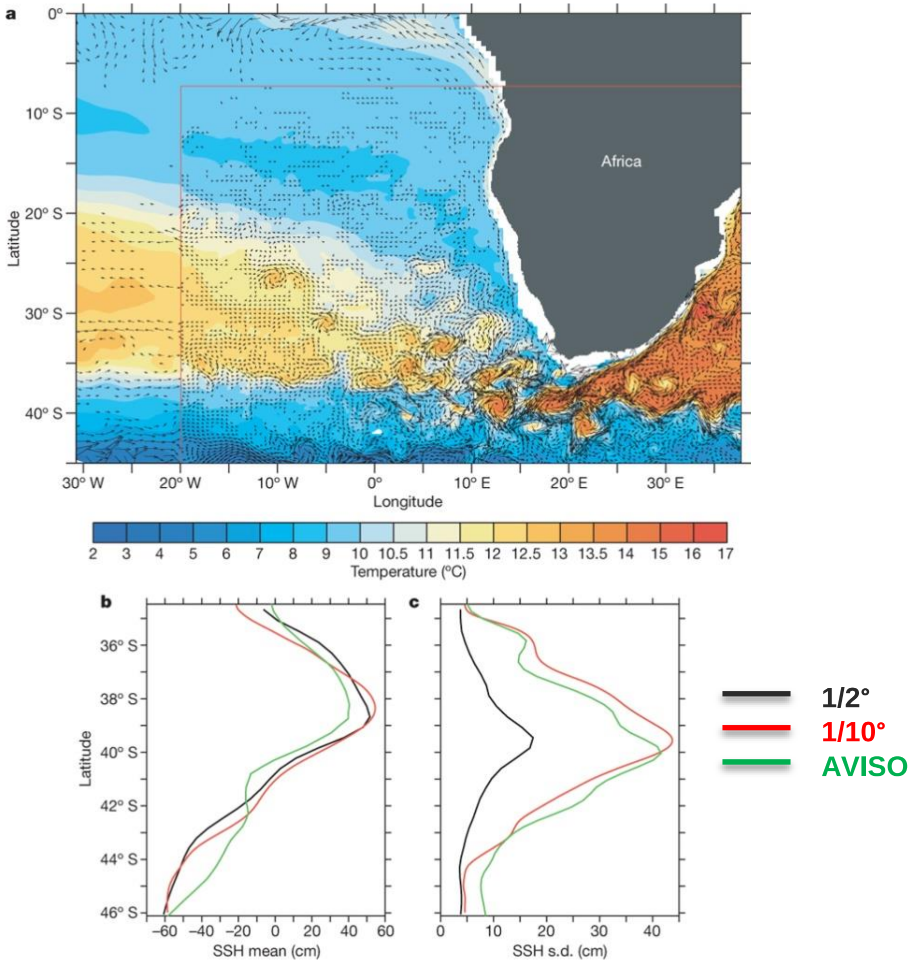




Chassignet and Xu, 2017

Eddies at the Agulhas retroflection

- Resolution is essential for capturing eddies shed from the retroflection
- Representing the Agulhas is key to the long term properties of a climate model

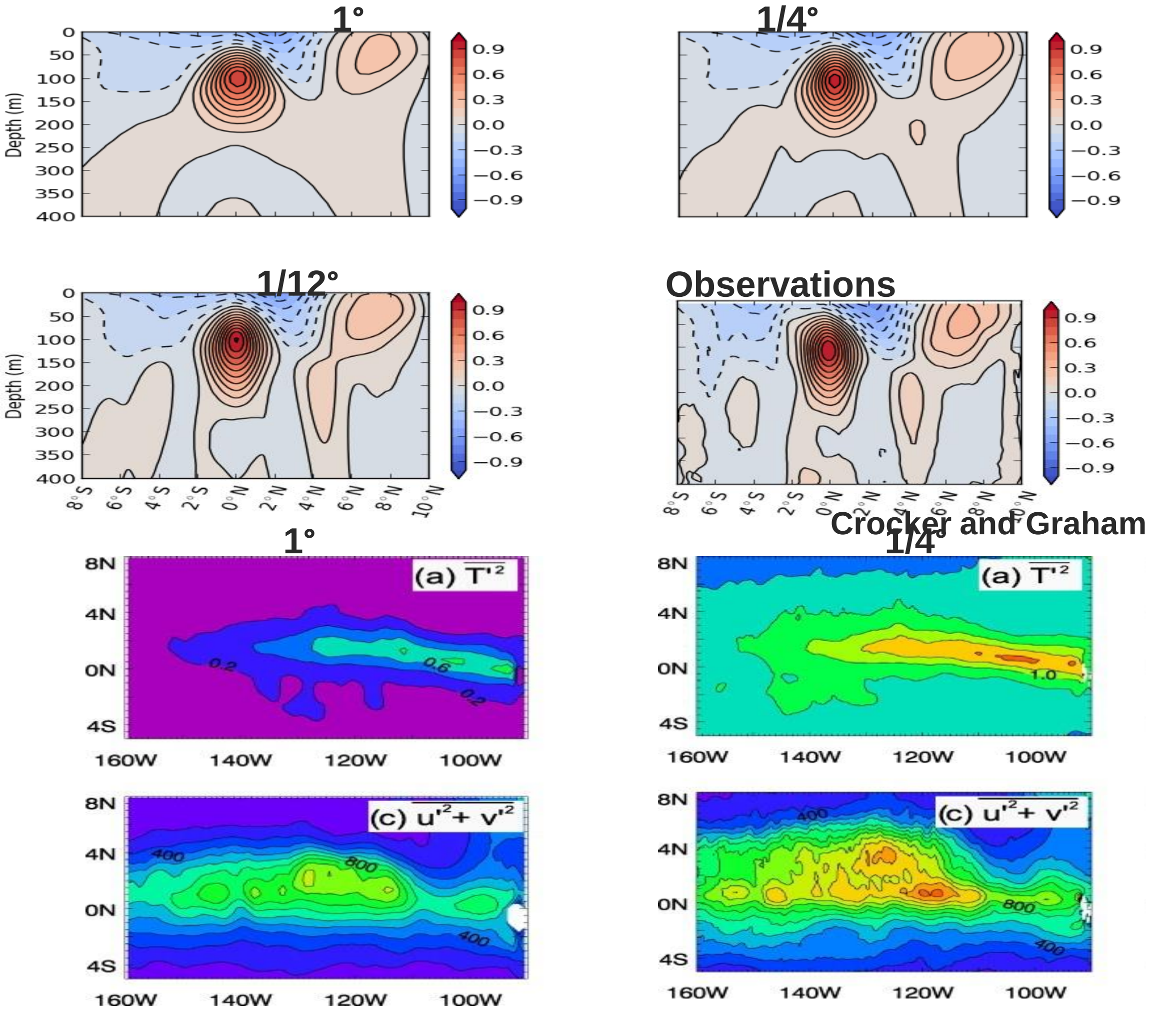


Biastoch et al., 2008

Met Office

Equatorial resolution

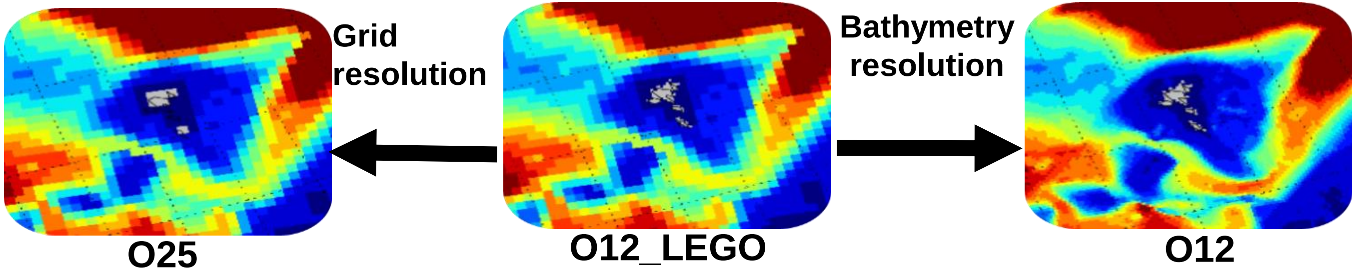
- Ocean model resolution will have little impact on El Nino once Kelvin and Rossby waves resolved (Guilyardi et al., 2004)
- Resolution is important for Tropical Instability Waves
- Heating by TIWs ~75% greater at high resolution during La Nina → reduced cold bias and enhanced asymmetry in ENSO

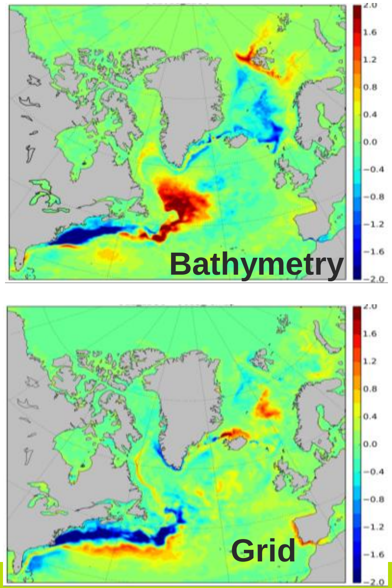


Graham, 2014

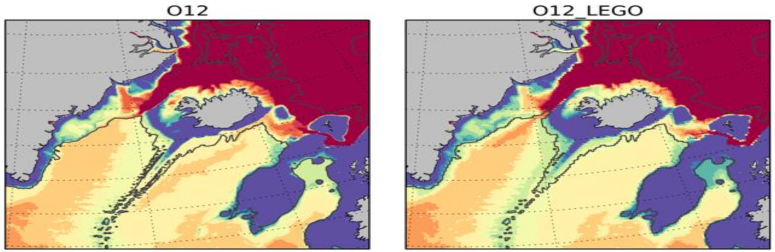
Topographic effects

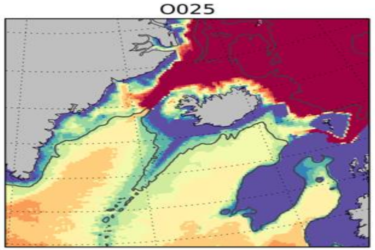
- Resolution of bathymetry is key factor in choice of the grid resolution.
- Overflows and Gulf Stream pathways very sensitive to the bathymetry.
- Strengthening of NADW cell is due to bathymetry (seen going from O12_LEGO to O12).



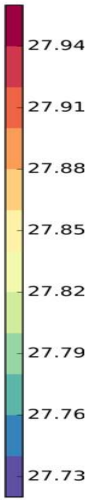


SST differences





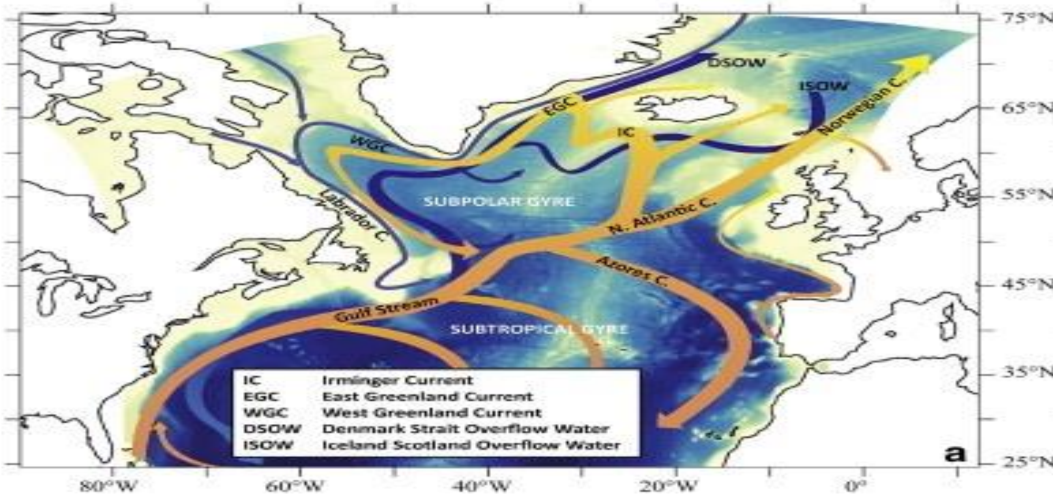
	Obs	025	12_L	12
DS	2.9	2.2	3.1	2.4
FBC	1.9	2.1	2.1	2.3



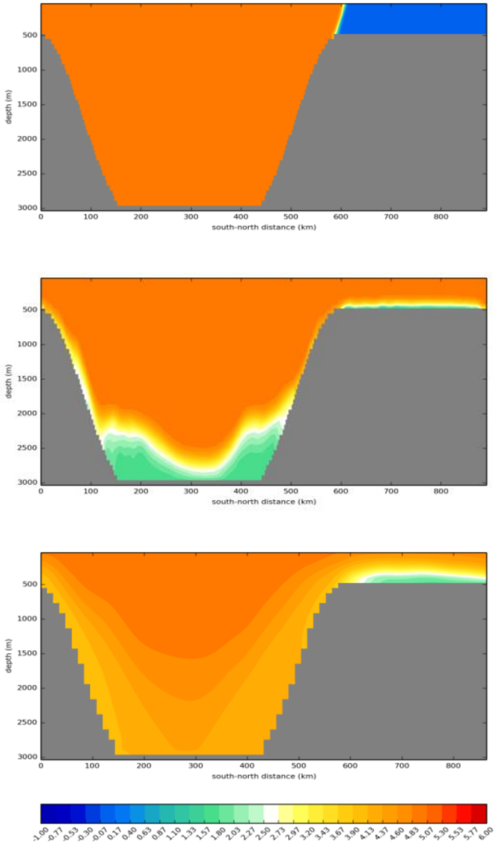
Mathiot et al., in prep.

Overflow resolution

- Horizontal and vertical resolution required to capture overflows
- Winton et al. (1998) estimate 3-5 km required horizontally and 30-50 m vertically
- Other approaches to vertical resolution later



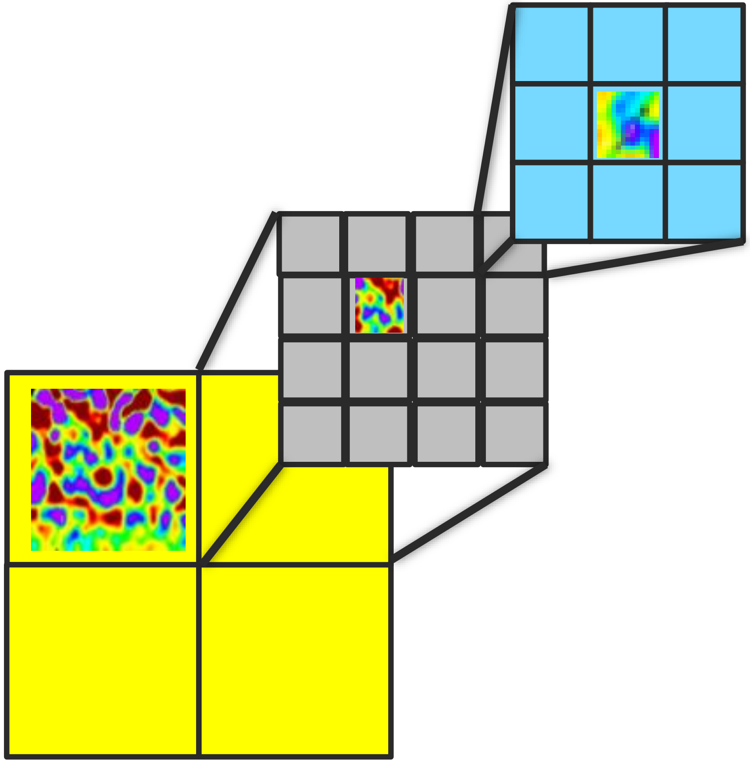
Marzocchi et al., 2015



Dave Storkey

Met Office

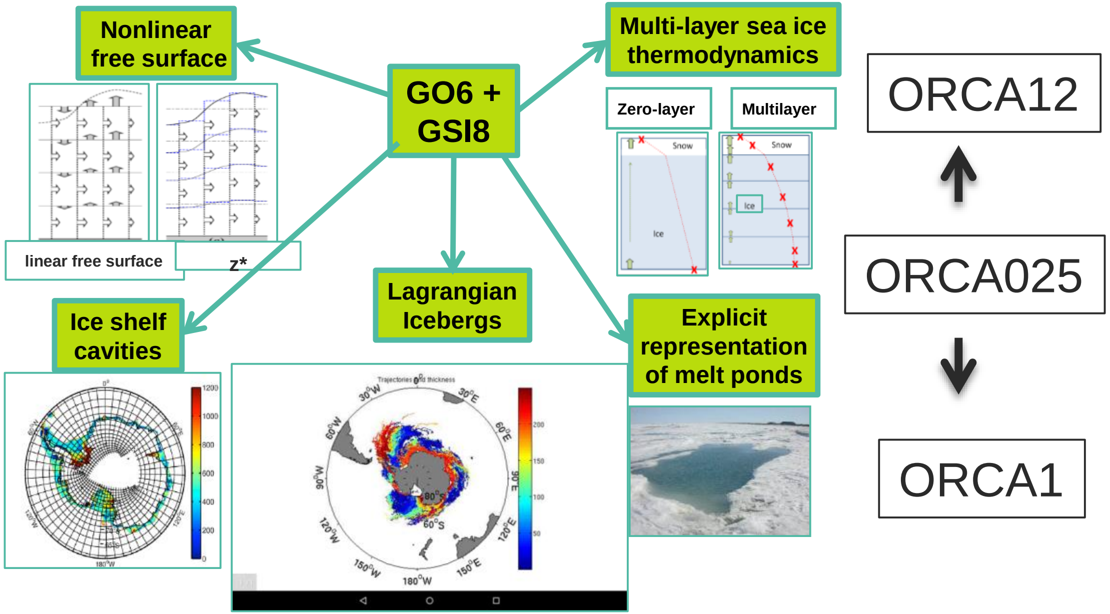
3. Traceable hierarchies and parameterisation



Met Office

Example: traceable hierarchy at GO6

Enabling better understanding of the impacts of resolution on climate



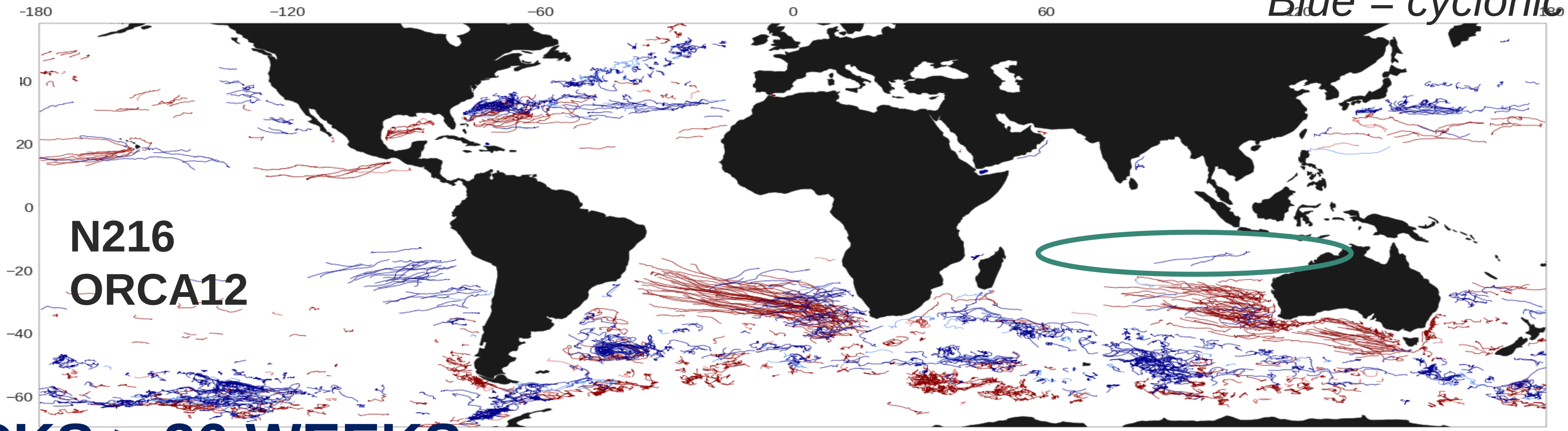
Storkey et al., GMDD

Met Office

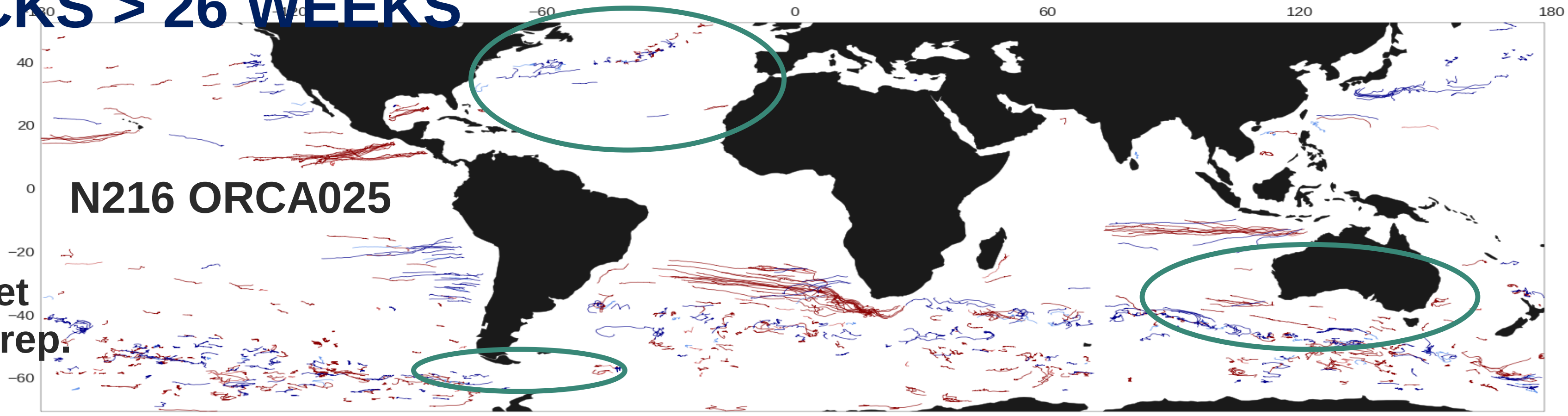
University of Reading

Mesoscale eddies

Red= anti-cyclonic
Blue = cyclonic



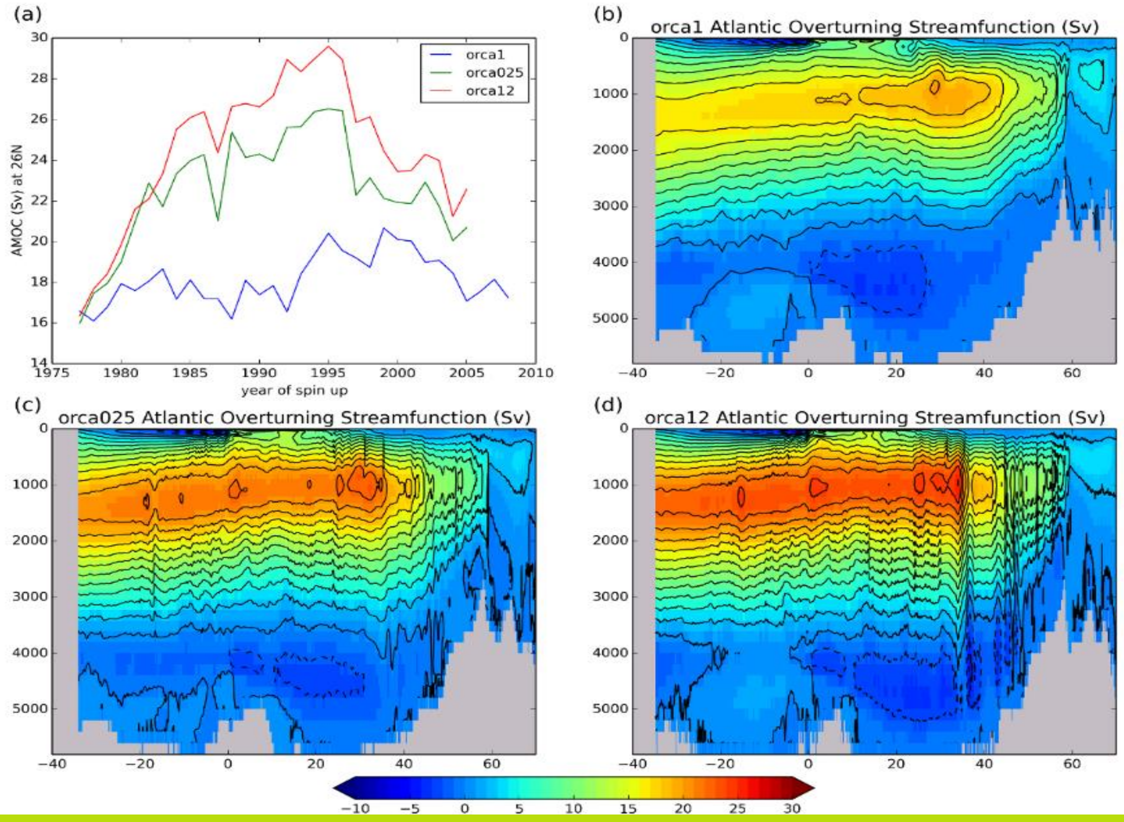
TRACKS > 26 WEEKS



Ashby et al., in prep.

AMOC in GO6 hierarchy

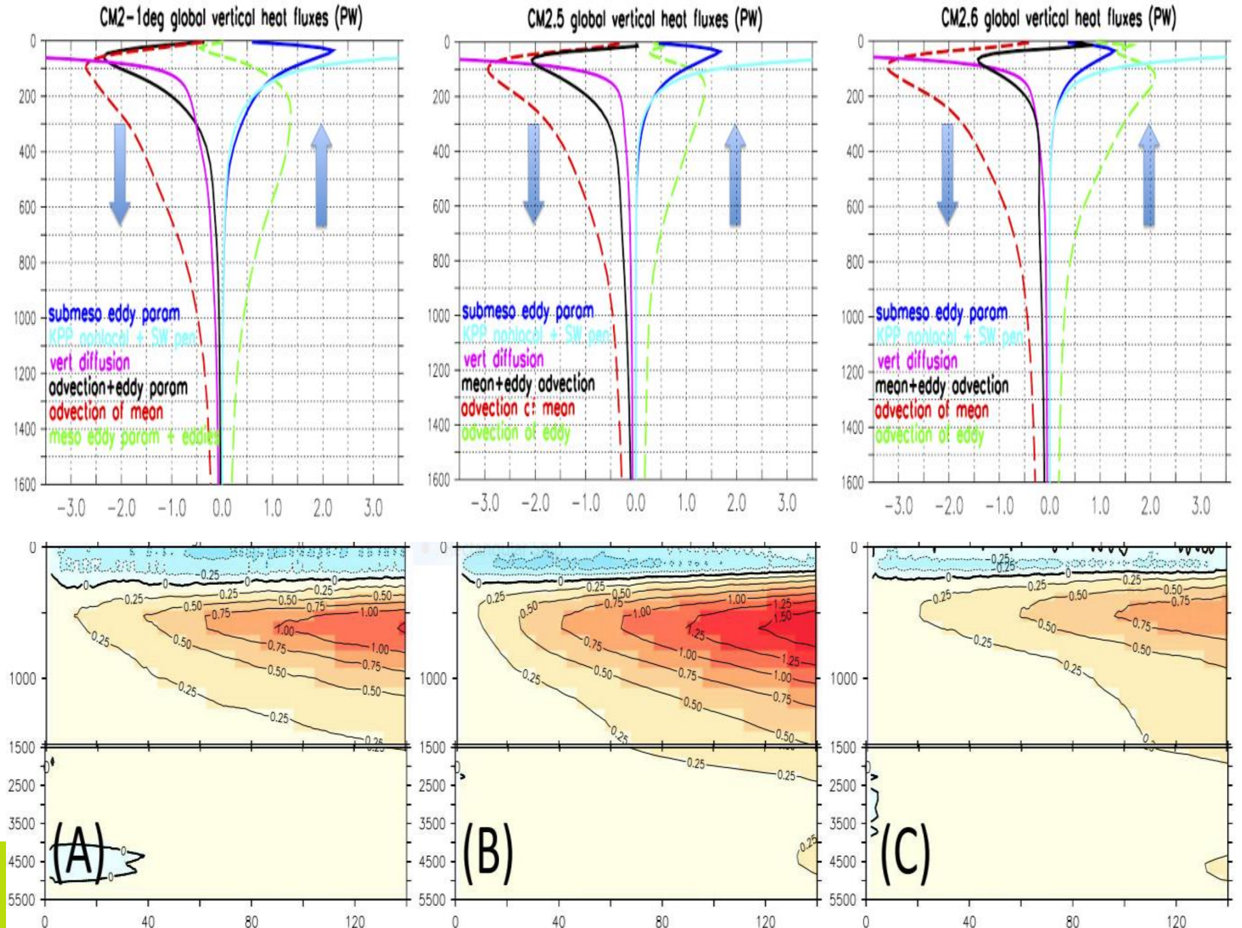
- Large variation in behaviour of AMOC across the hierarchy
- Higher resolutions overshoot but still tend to a higher AMOC
- Model dependent behaviour? Highly sensitive to Labrador Sea convection



Storkey et al., GMDD

Role of eddies in the heat budget

- Eddies play an important role in the heat budget - globally transporting heat upwards
- Southern Ocean: eddy energy penetrates deep into water column
- Mid-latitude gyres: eddy activity compensates Ekman pumping
- Important consideration for spinup and model biases



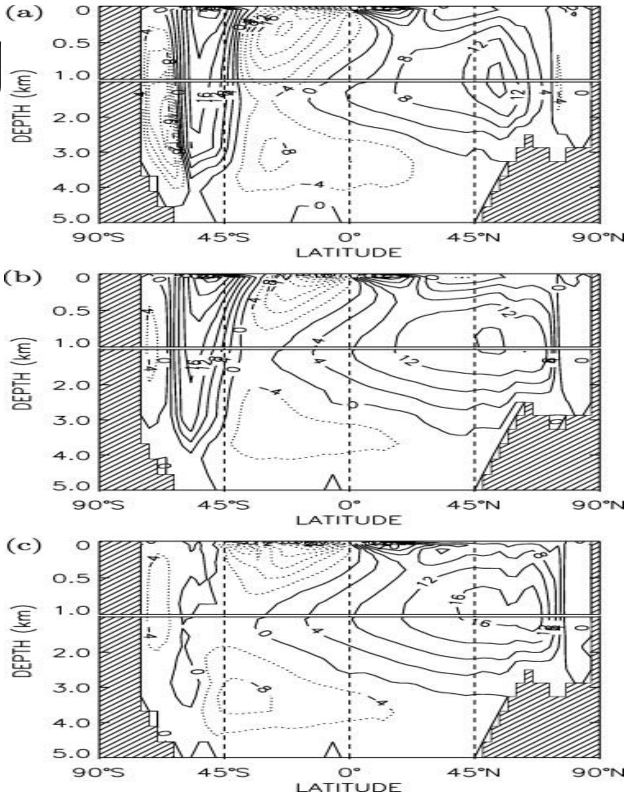
Griffies et al., 2015

Parameterising eddies

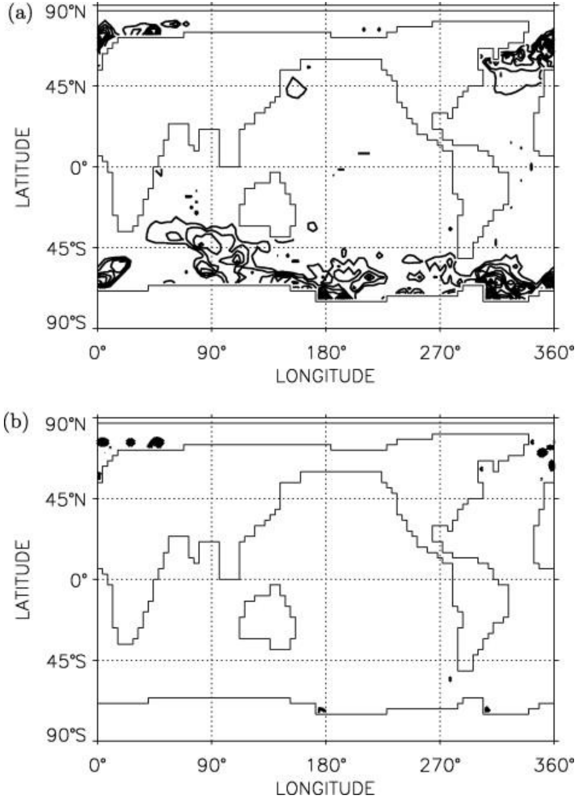
$$\frac{\partial}{\partial t}h_{\rho} + \nabla.(\mathbf{u}h_{\rho}) = \nabla.(\kappa\nabla h)_{\rho}$$

$$u^{*} = -\frac{\kappa}{\bar{h}}\nabla_{\rho}\bar{h}$$

K =Thickness diffusion



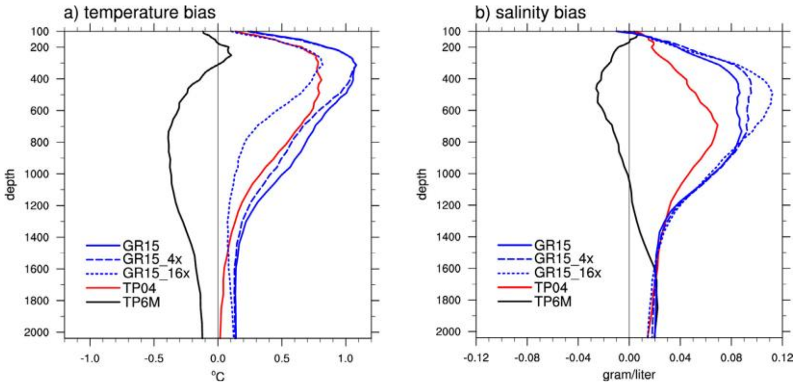
Gent & McWilliams, 1990



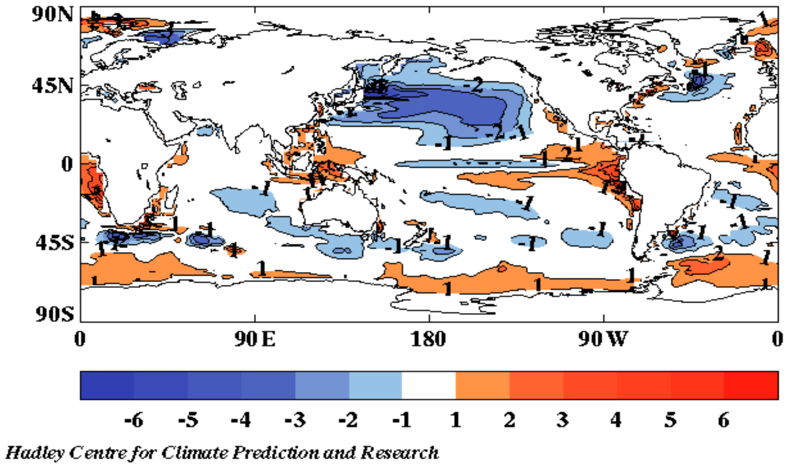
Danabasoglu et al., 1994

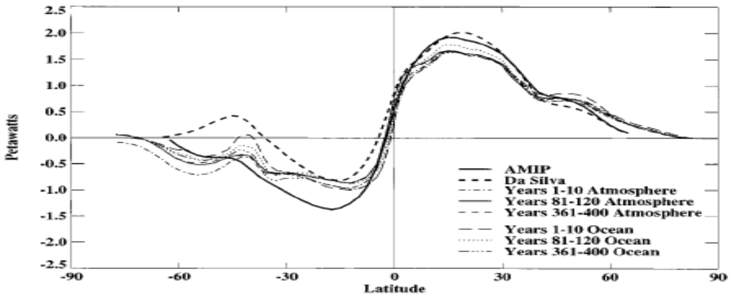
Impacts of GM parameterisation

- GM allows coupled model to be run without flux adjustment-ocean can transport sufficient heat
- Salinity also affected by GM-increasing GM reduces temperature biases but increases salinity biases



Von Storch et al., 2016



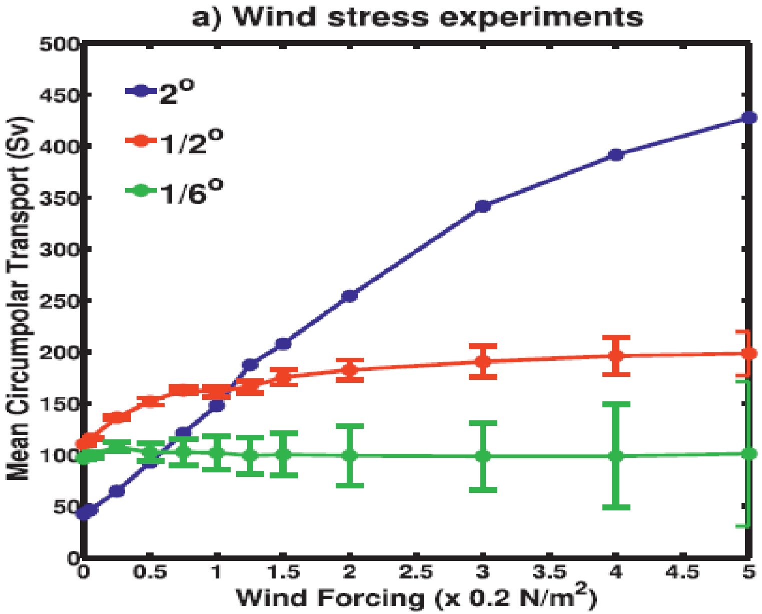


$$\frac{\partial \theta}{\partial t} + \oint v\theta dS = \int Q dA$$

Gordon et al., 2000

Eddy saturation/compensation

- Eddy saturation means that the ACC doesn't spin-up in response to increased winds
- Climate change response of low resolution models could be compromised unless GM parameterisation can account for this
- Subject of current research (David Marshall)

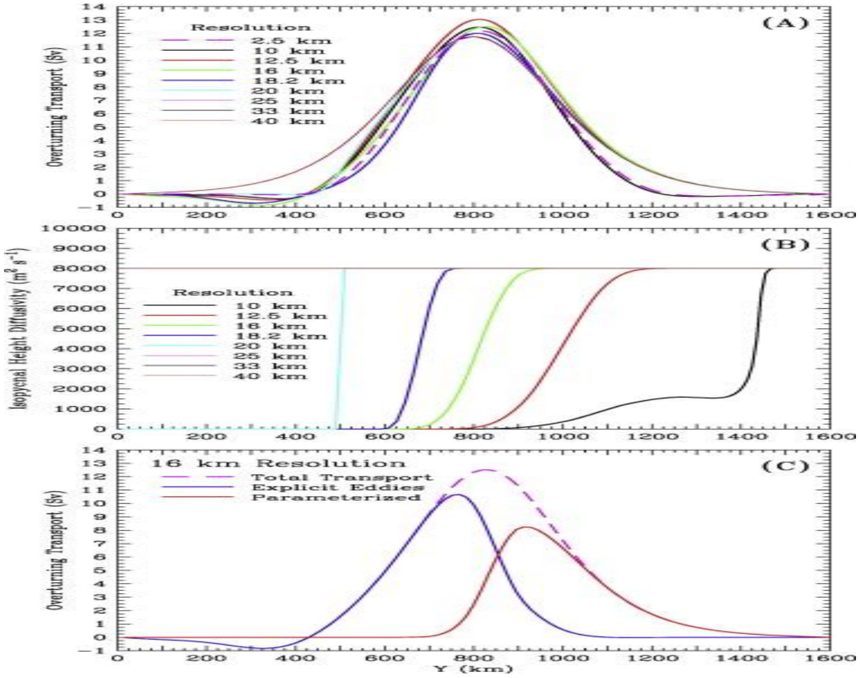


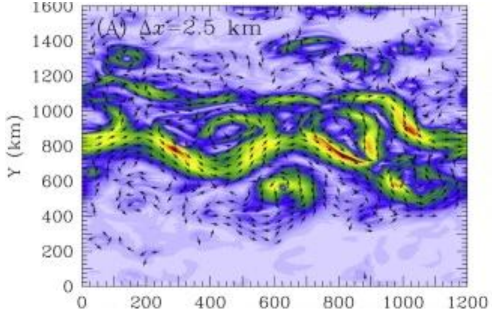
Munday et al., 2013

Met Office

Parameterise as a function of resolution?

- Can you switch eddy parameterisation on only when resolution is insufficient to parameterise eddies?
- Switch on GM when Rossby radius < 2*dy

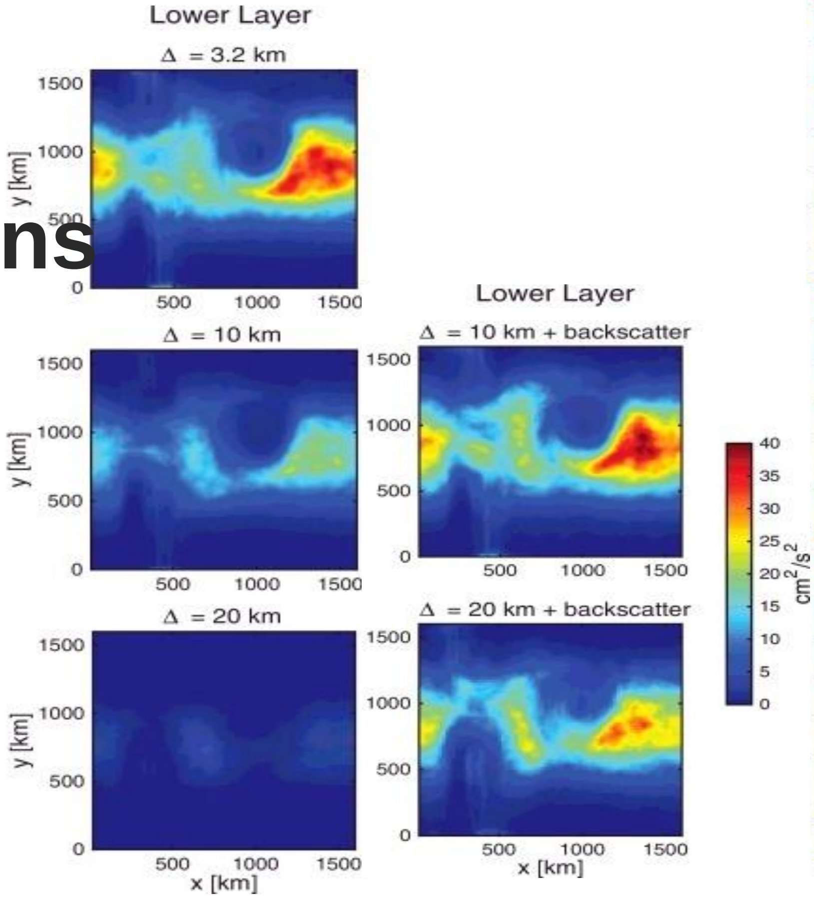




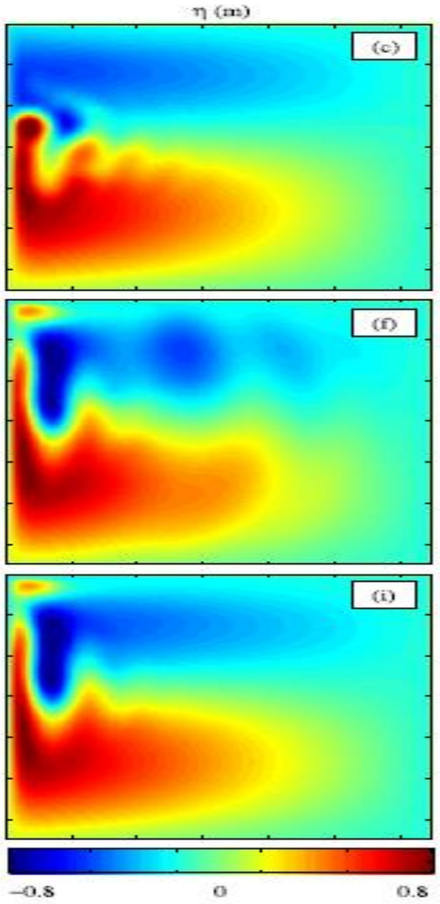
Hallberg, 2013

Scale-aware parameterisations

- Represent eddy momentum fluxes via backscatter parameterisation
- Ideas based on reinjecting energy that would have been dissipated at the gridscale back to the large-scale
- Negative Laplacian or non-Newtonian stress tensor



Jansen et al., 2015



Cooper and Zanna, 2015

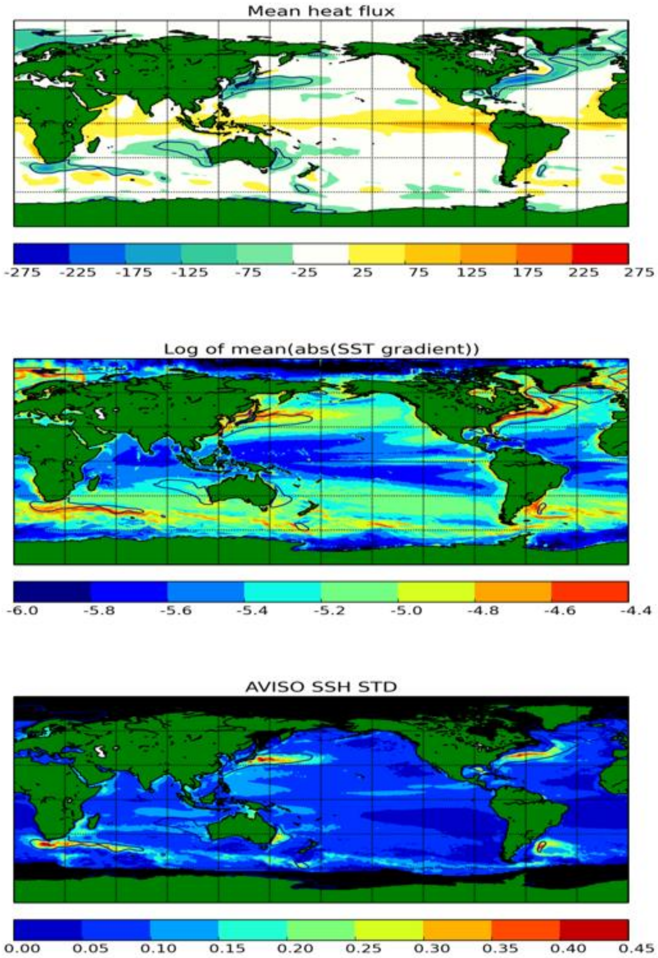
Met Office

4. Sensitivity to resolution in coupled systems

- Ocean resolution is likely to affect both atmosphere and ocean

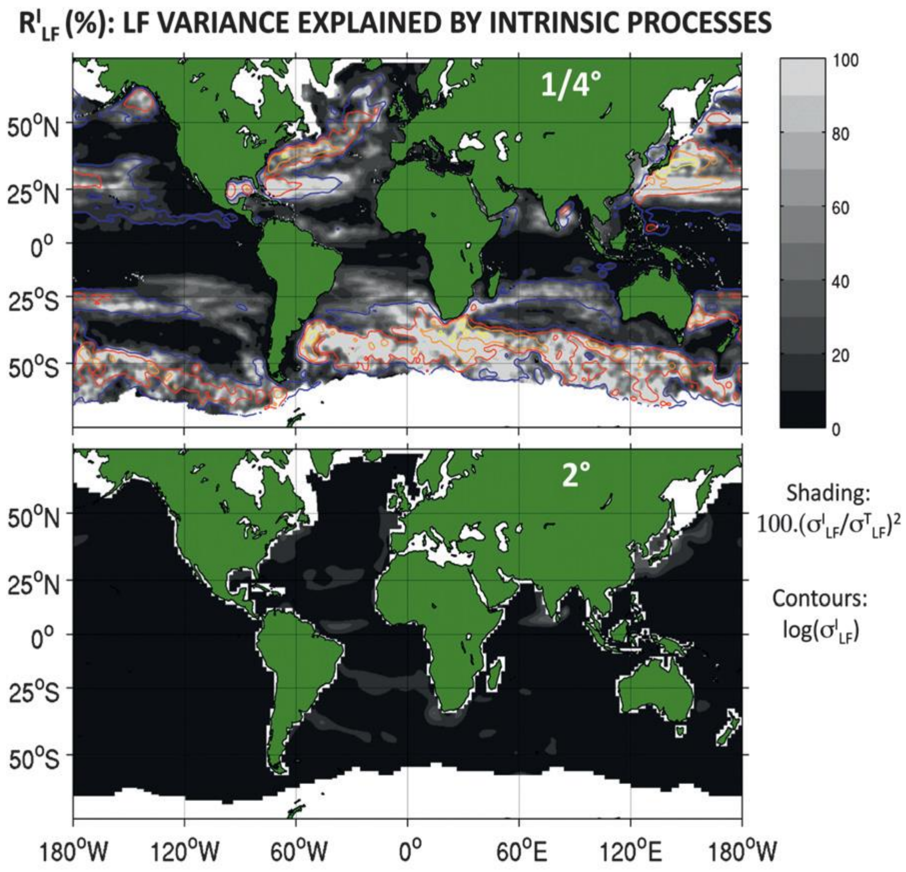
- Largest air-sea fluxes in frontal regions with high EKE

- Evidence for impacts in the coupled system



Intrinsic variability

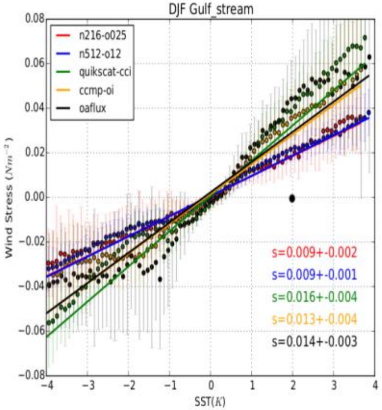
- Ocean intrinsic variability forces low frequency ocean variability in eddying regions
- Can be seen in ¼ degree model but not 2 degree model
- Potential forcing of atmosphere in these regions

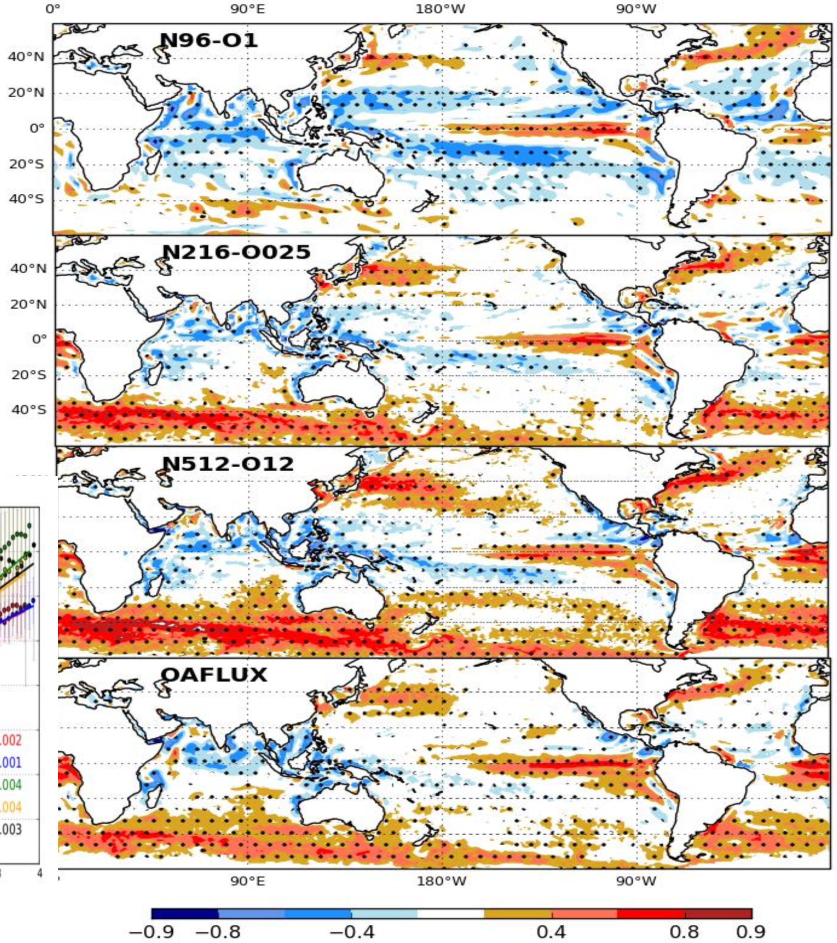


Penduff et al., 2011

SST-windstress relationship

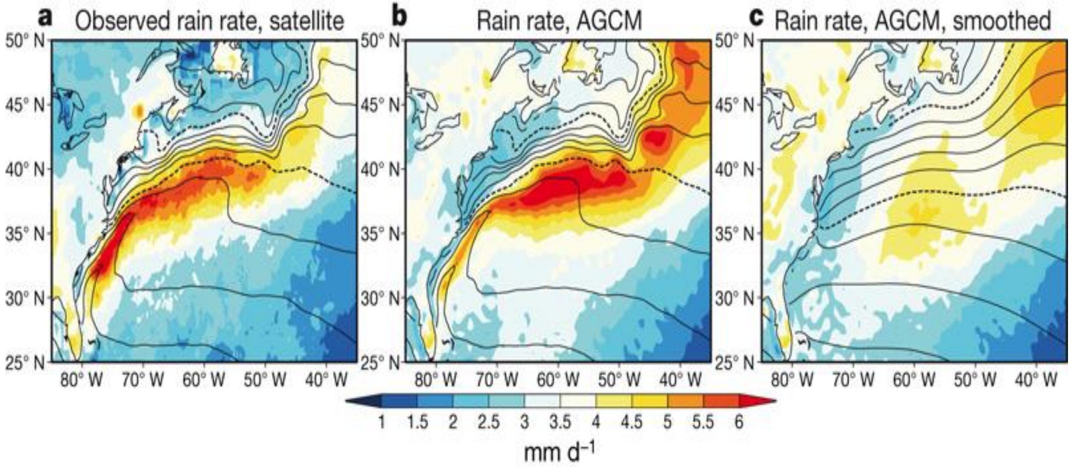
- Positive correlations indicate where ocean leads atmosphere
- Ocean becomes more important as resolution increases
- Once eddies and fronts present, not strongly sensitive to resolution
- Deficiency in physics of atmospheric boundary layer parameterisations? (Song et al., 2009)

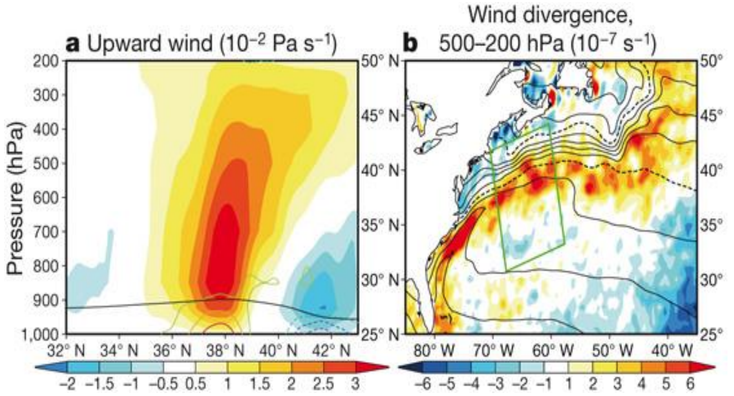




Impact of boundary currents on atmosphere

- Modelled rain rates depend on resolution of SST field
- Effects may be seen into upper troposphere



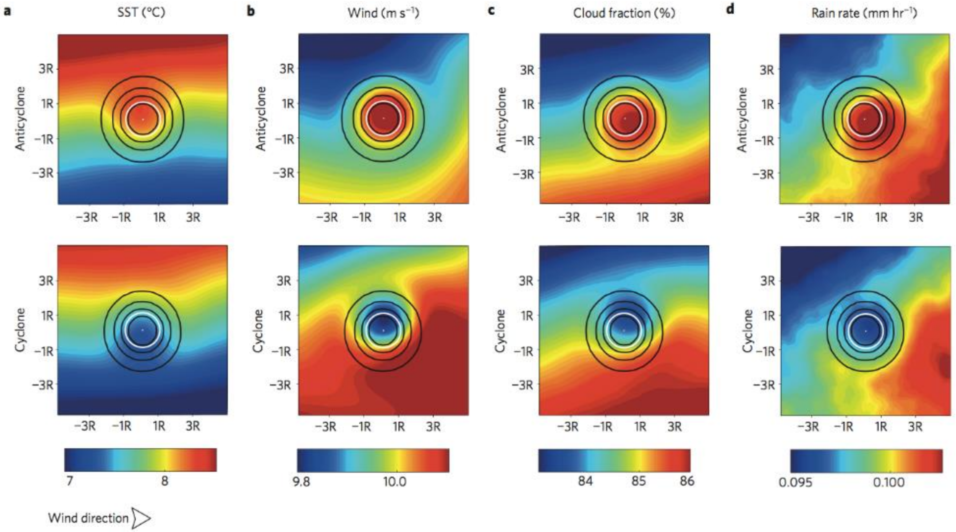


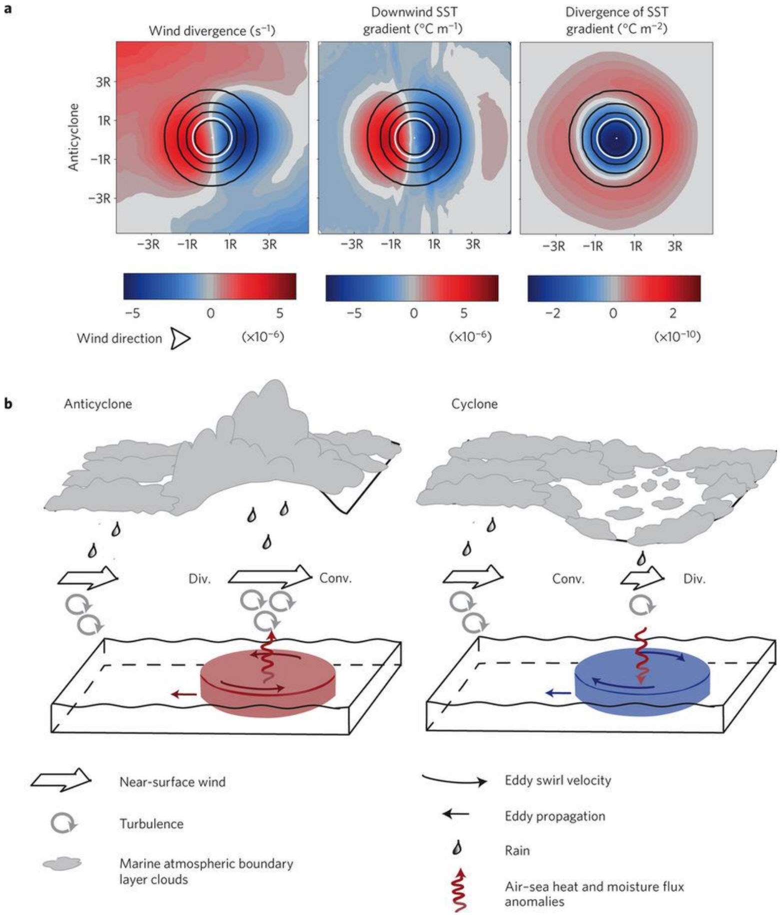
Minobe et al. 2008

Met Office

Eddies imprint on atmosphere

- Imprint of eddies seen in atmosphere - downwind momentum mechanism appears to dominate
- Do we see such a strong coupling in the model and does it matter which grid fluxes are calculated on? (S. Ashby)

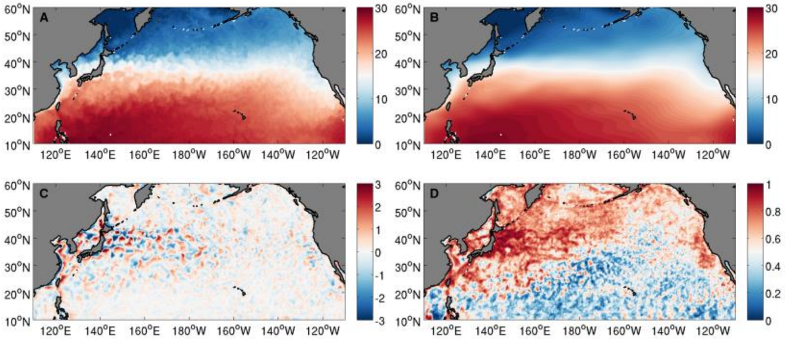


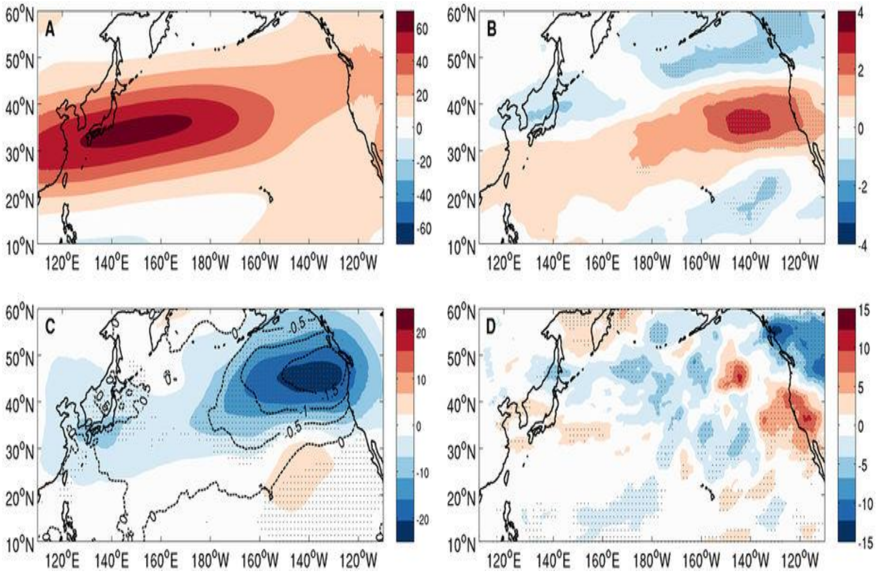


Frenger et al., 2013

Eddies affecting atmosphere circulation

- Differences between models with actual SST and SST filtered to remove eddies
- Difference in wind, SLP and transient KE





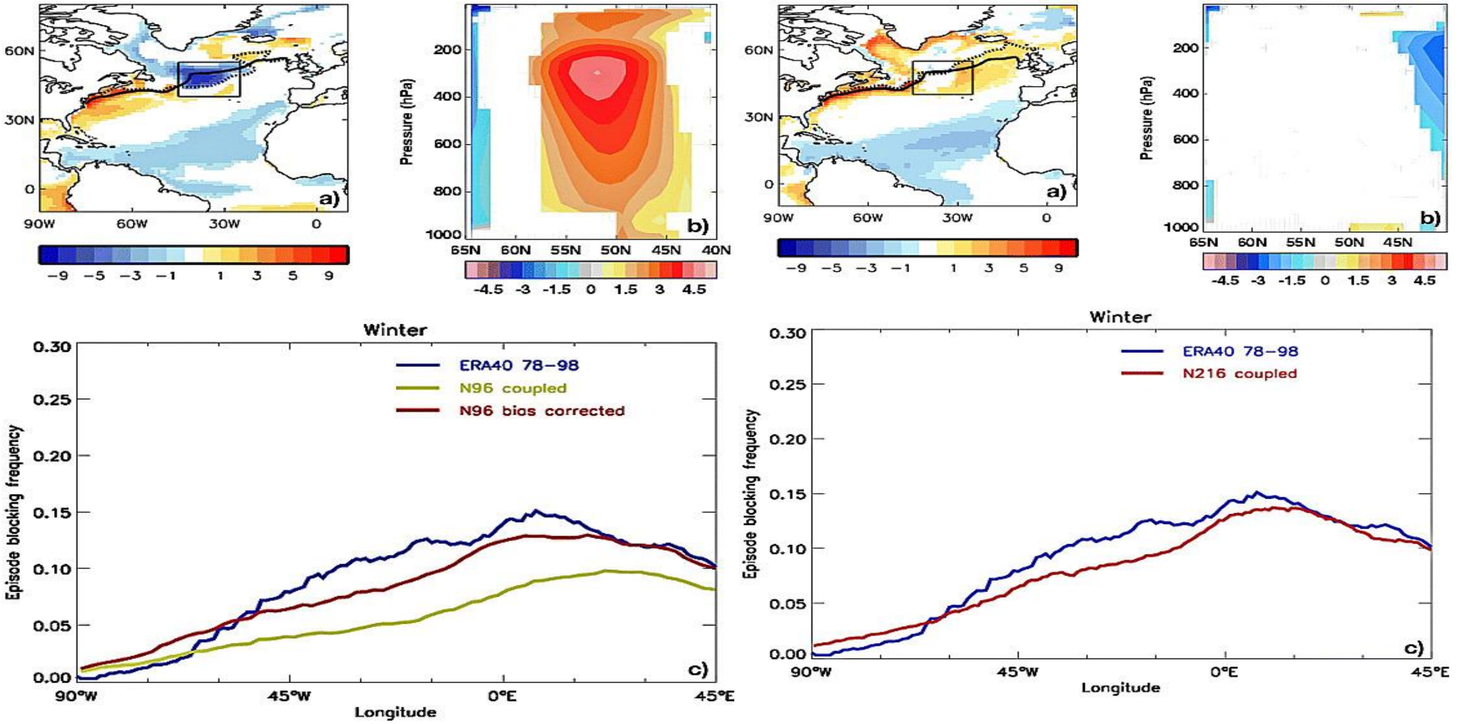
Ma et al., 2015

Improved winter blocking at eddy permitting resolution

Met Office

Reduction in SST bias moving from 1 degree to ¼ degree improved blocking

Bias largely due to steering of North Atlantic current

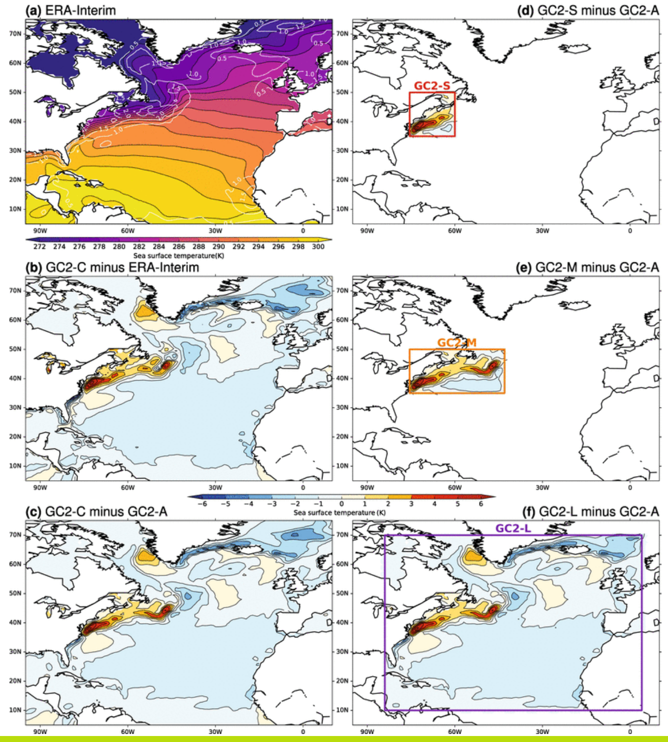


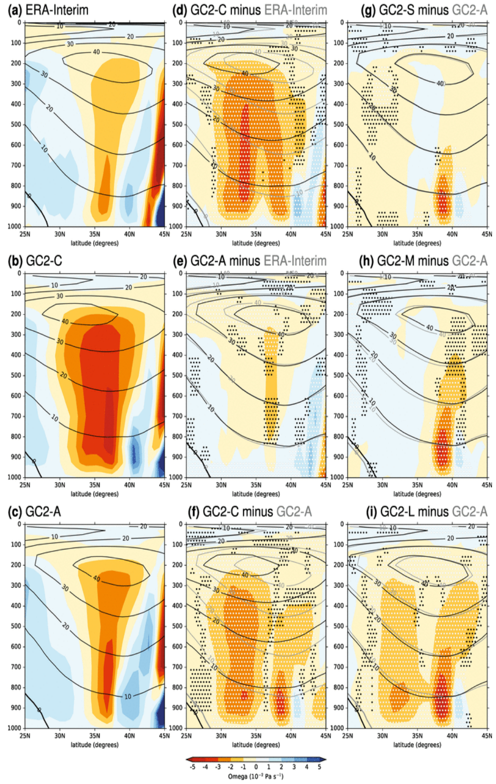
Scaife et al., 2011

Met Office

Atmosphere response to SST errors

- SST errors due to topographic steering
- Response: (1) meridional heat advection by a mean wind anomaly; (2) meridional heat advection by the transient eddies; and/or (3) ascent and the associated adiabatic cooling over the western boundary currents (WBC) and their extensions
- 3 dominates in these experiments

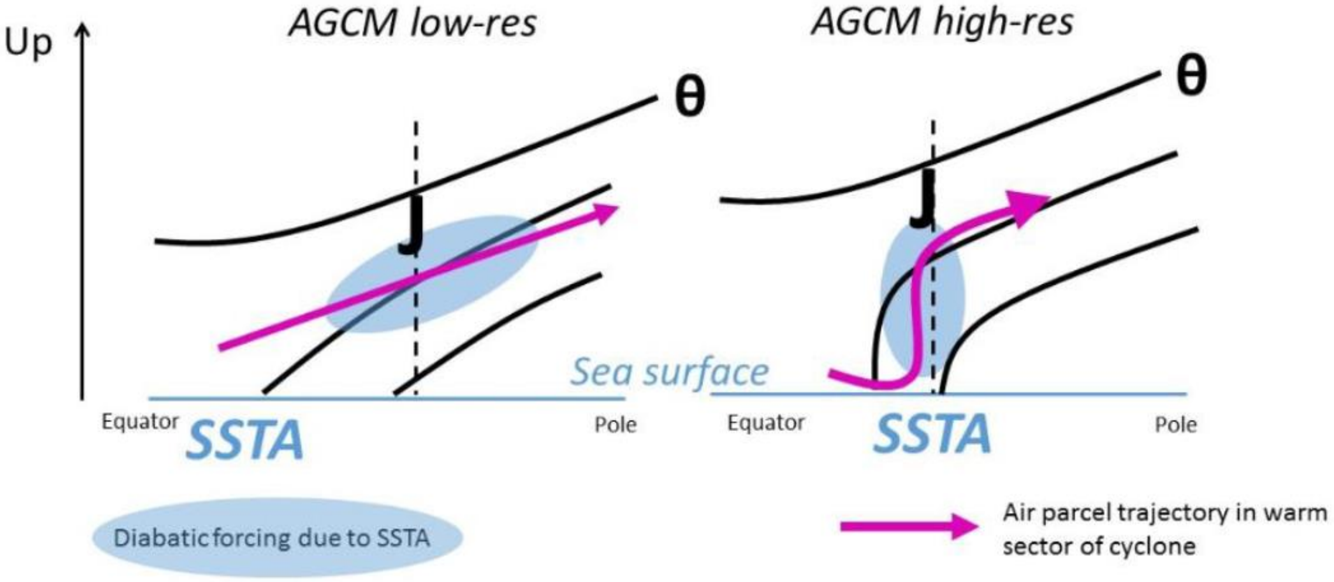




Lee et al., 2017

Met Office

Emerging paradigm

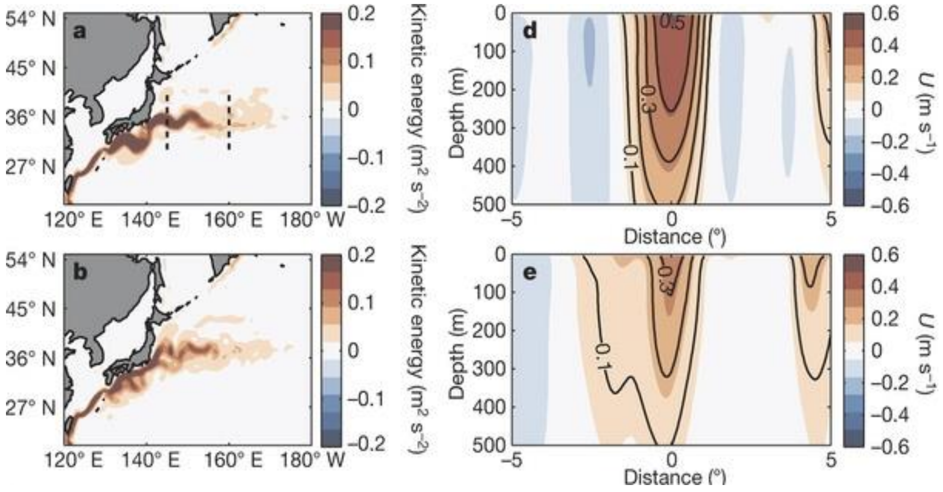


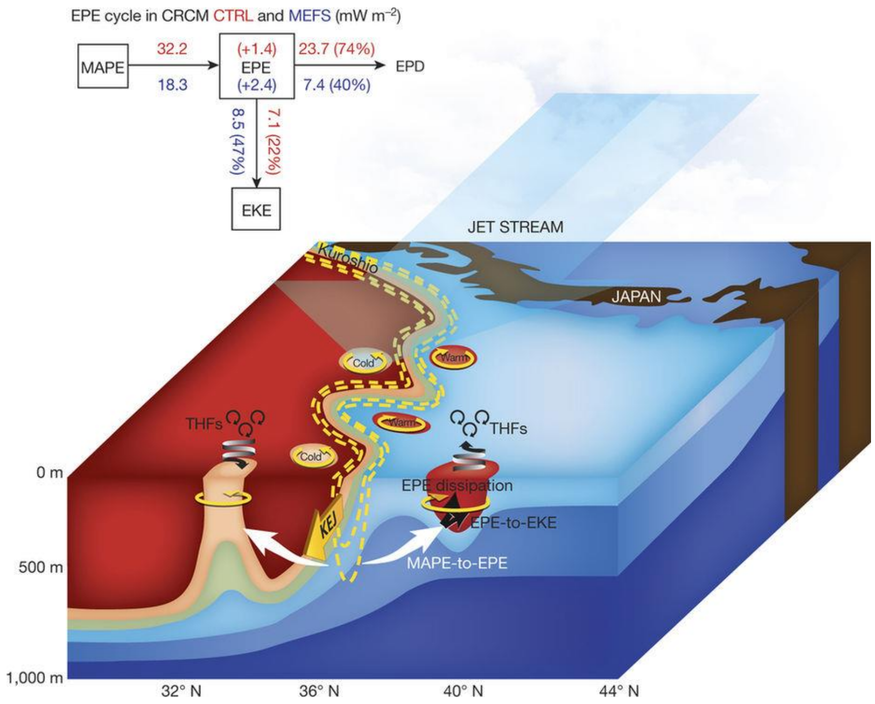
Need sufficiently high resolution in atmosphere model to capture connection to upper tropsphere

Arnaud Czaja

Impact of eddy-atmosphere interaction on the ocean

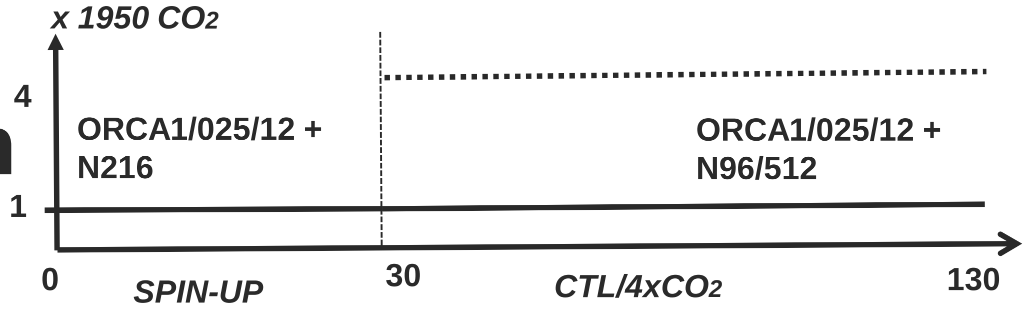
- Interaction of eddies with the atmosphere impacts on the ocean circulation





Ma et al., 2016

Exploring resolution



- Resolution hierarchy of GC3.
- Ocean components is GO6 – NEMO at ORCA1 (L), ORCA025 (M) and ORCA12 (H).
- Atmosphere resolutions – 150km (N96; L), 60km (N216; M), 25km (N512; H).
- Control and 4xCO_2.

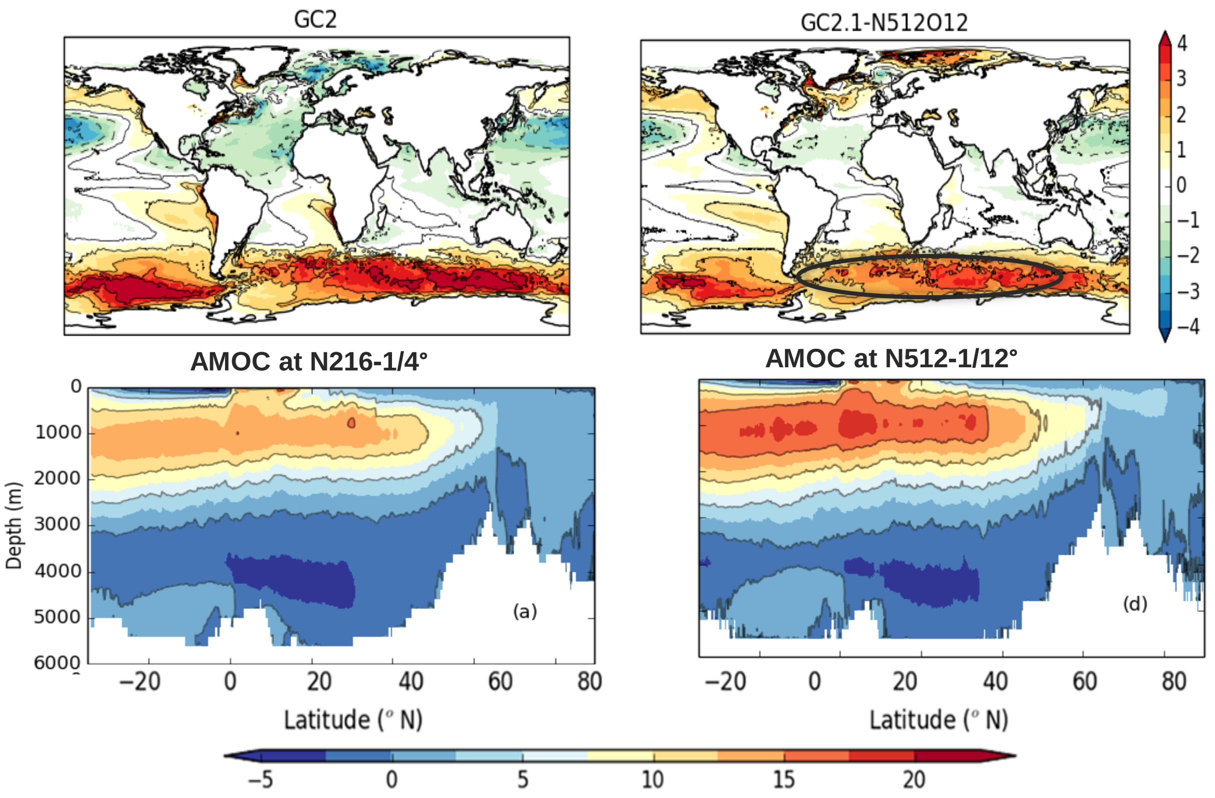
	150km N96 L	60km N216 M	25km N512 H
ORCA1 1 deg L	DECK/MIPs UKESM PD, *CTL, HIST, 4XCO2*	*CTL*	
ORCA025 1/4 deg M	PD	DECK/MIPs PD, *CTL, HIST*	*CTL, HIST, 4XCO2*
ORCA12 1/12 deg H		*CTL*	PD, *CTL, HIST, 4XCO2*

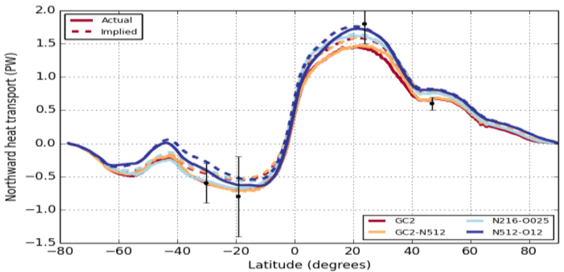
GC3: Williams et al., JAMES, in press
GO6: Storkey et al., GMDD
HighRes-MIP: Haarsma et al., GMD, 2016
EU-PRIMAVERA, NERC ACSIS

Met Office

Impact of resolution

- GC2 coupled model
- Changes in SST biases
- Stronger AMOC at ORCA12
- Associated with interhemispheric shift in SST and ocean heat transport
- Continuing work with longer control and transient experiments



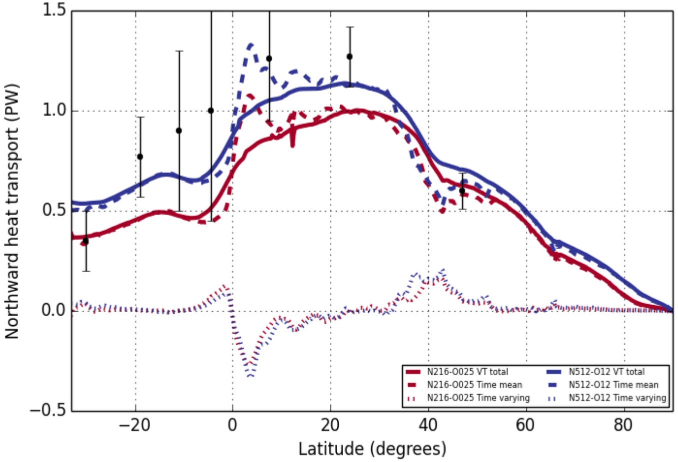


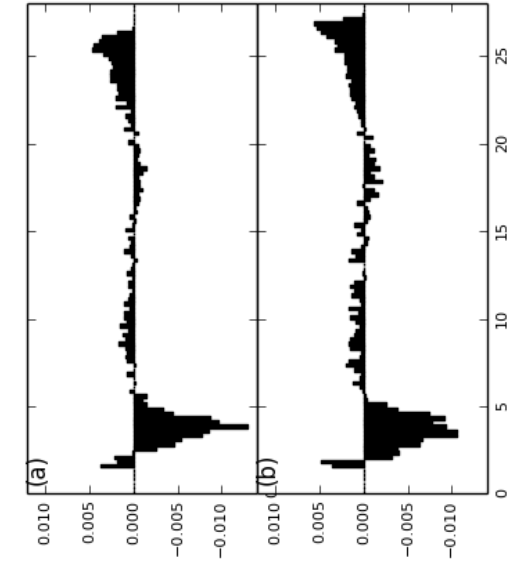
Hewitt et al., 2016
Roberts et al., 2016

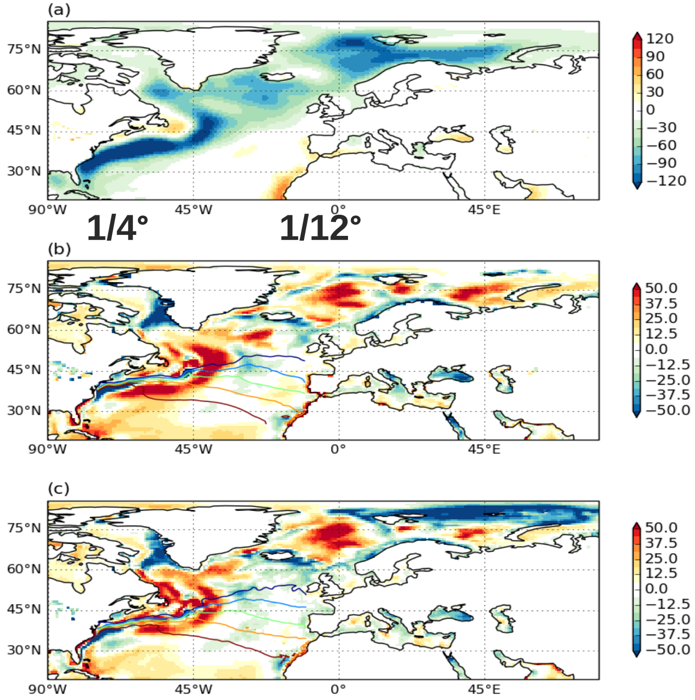
Met Office

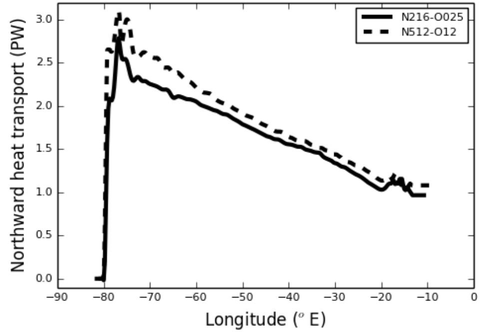
Impact on mean state

- Improved northward heat transports
- Linked to stronger Gulf Stream
- Impact on SST field reduces surface heat flux error





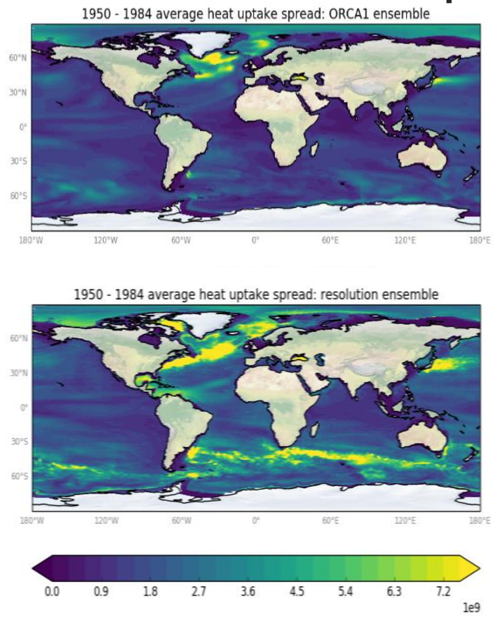


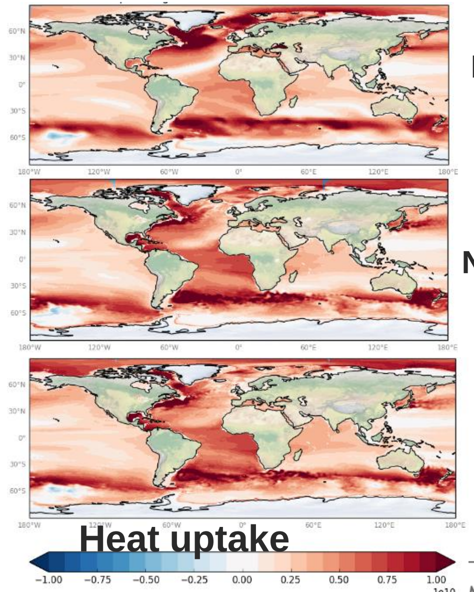


Roberts et al., 2016

Preliminary: Sensitivity of climate change response to resolution

Resolution vs ensemble spread



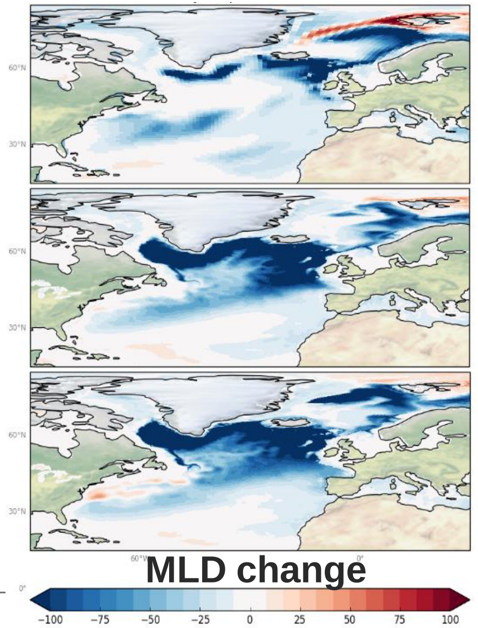


Heat uptake

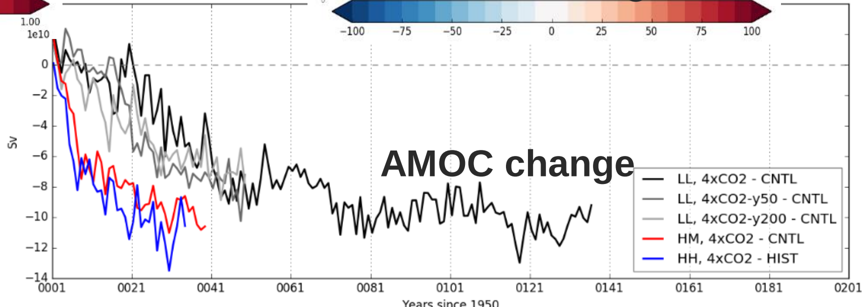
N96-ORCA1

N512-ORCA025

N512-ORCA12



MLD change

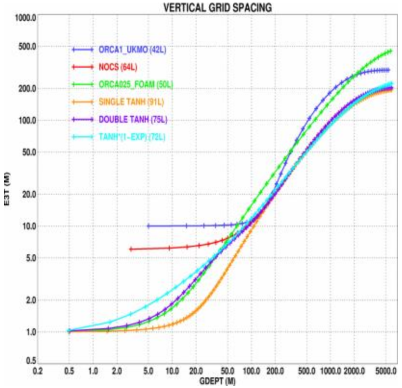


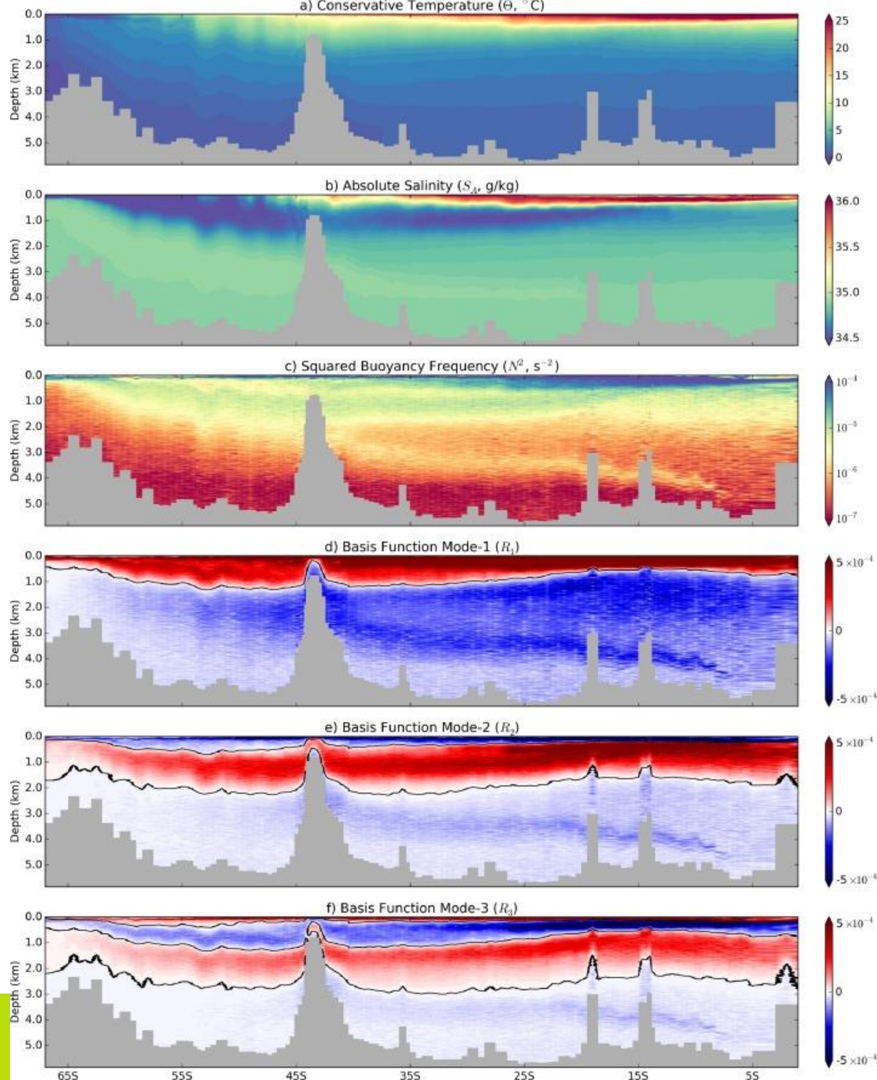
AMOC change

Daley Calvert, Pierre Mathiot, Mike Bell, Malcolm Roberts, Helene Hewitt

5. Vertical resolution/ coordinates

- Choose vertical resolution to allow the baroclinic models to be represented
- Need at least 3 grid points between modal crossings
- 75 levels turns out to be sufficient for 1st and 2nd modes



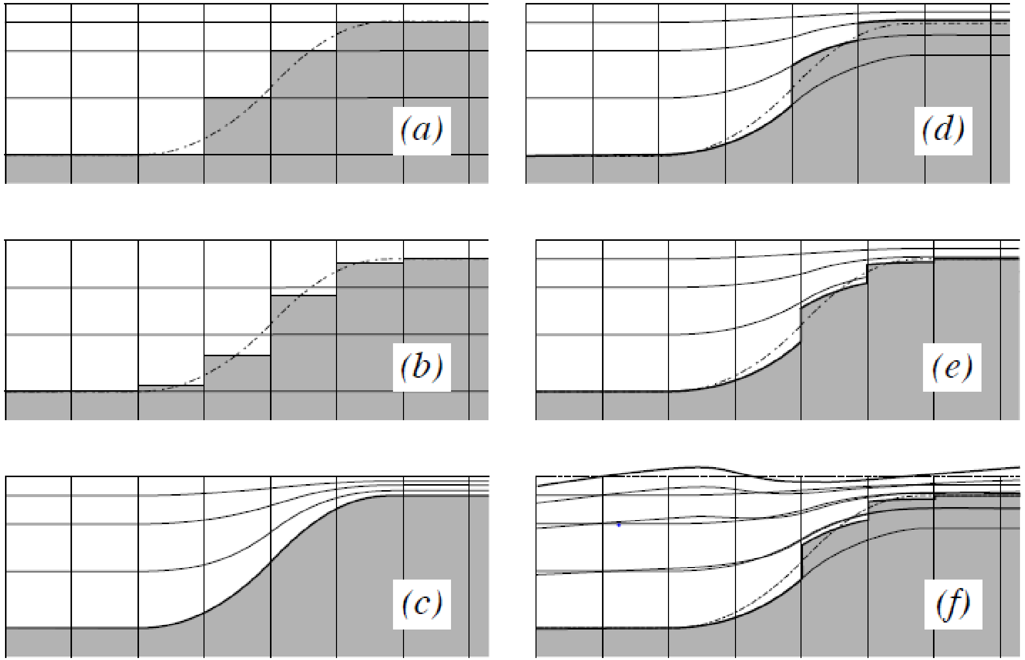


$$R_m(z) \approx -\left(\frac{c_m N(z)}{g}\right) \cos\left(\frac{1}{c_m} \int_{-H}^{z} N(z)\, dz\right).$$

Stewart et al., 2017

Other coordinate choices

- Z (with partial steps)
- S (terrain following) (with partial steps and combined with z)
- Non-linear free surface
- Advantages and drawbacks with all approaches but try to make best choice for the application
- In particular, s coordinates may be a good approach in the overflows to provide vertical resolution

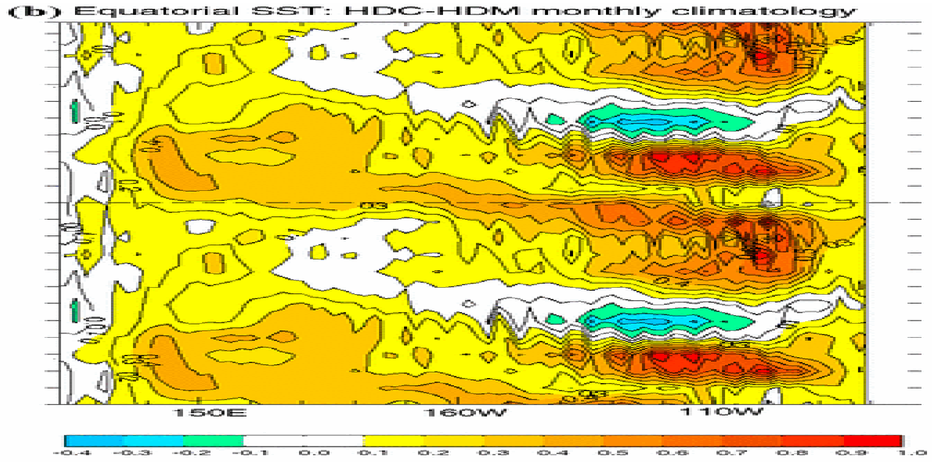


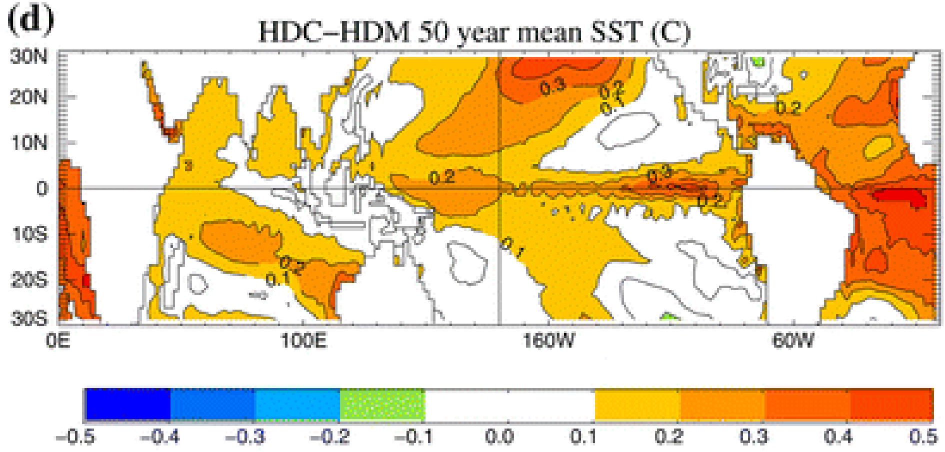
Madec et al., 2016

Met Office

Vertical resolution in coupled models

- Large-scale warming of SST
- Enhanced seasonality in Tropics





Bernie et al., 2008

6. Summary

- Tropics and boundary currents suggest a minimum 1/4° horizontal resolution-although note that this resolution is deficient in terms of heat budget and big uncertainties as to parameterisation approach
- Benefits of eddy-resolving include eddies, fronts and topographic control. Emerging results are likely to lead to improved parameterisations or improved evidence for high resolution
- Traceable model hierarchies allow systematic assessment and greater understanding
- Evidence that coupled processes associated with boundary currents, fronts and eddies affect the mean state of both ocean and atmosphere in coupled models
- Vertical resolution considerations are resolving diurnal cycle (1m near surface) and baroclinic modes. Overflows require specific consideration (coordinates or parameterisation)

Resolution choices for different applications

Short range ocean forecasting: resolution to resolve mesoscale features

Seasonal: sufficient ocean resolution for accurate atmospheric circulation, Equatorial regions but also mid-latitudes

Decadal: ocean memory becomes important – need accurate circulation particularly in subpolar gyre and overflows

Climate: long-term heat and freshwater budget and circulation to get accurate response (including impact of eddies)

Met Office

Questions for physics dynamics coupling

- Can parameterisations be improved to mitigate deficiencies of models that aren't eddy resolving? Can scale-aware parameterisations in the ocean impact on coupled response?

- How should resolution of both atmosphere and ocean components be chosen and do we need to think about the resolution on which fluxes are calculated?

- Will atmospheric boundary layer parameterisations/resolution need to be revisited in light of coupled processes?

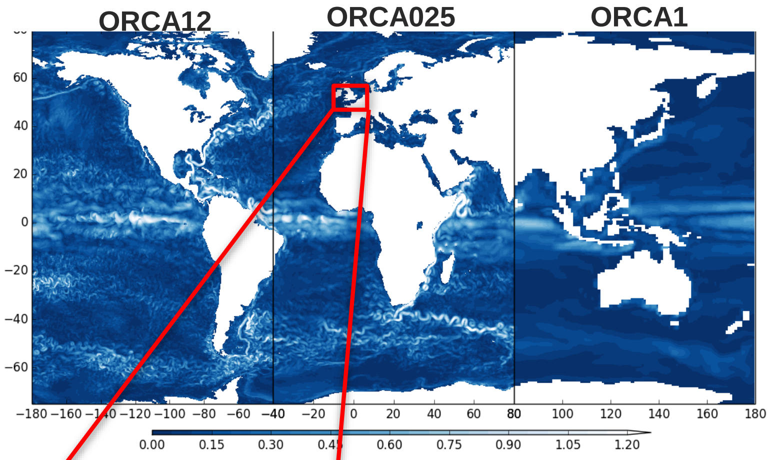
The next frontiers in global ocean models

Eddies and shelf processes

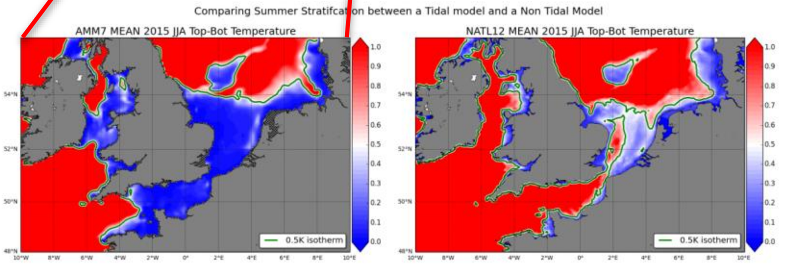
Shelf sea enabled global model

- Nutrient and carbon exchange with global ocean
- Global marine impacts incl. coastal sea level
- Marine methane release

Interactions at the kilometric scale and in the shelf/near shelf region are areas of new research



High resolution improves currents, eddies, open ocean processes BUT...



Stratification (JJA) from shelf 1/15°°

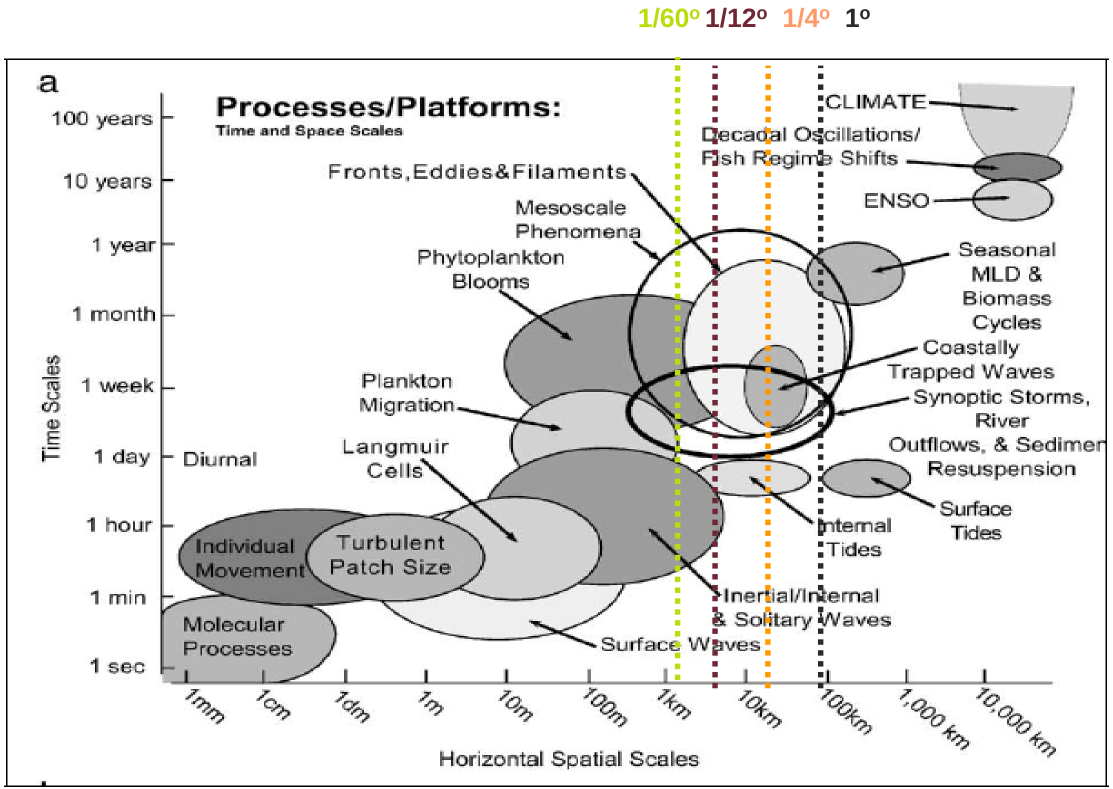
Stratification (JJA) from global 1/12°°

...need tides and shelf processes to capture well-mixed regions

Met Office

Processes models resolve

- Typical resolution of ocean models spans the regime of mesoscale phenomena
- Need to parameterise below the resolved scales
- Key is to understand the compromises in the choice of resolution



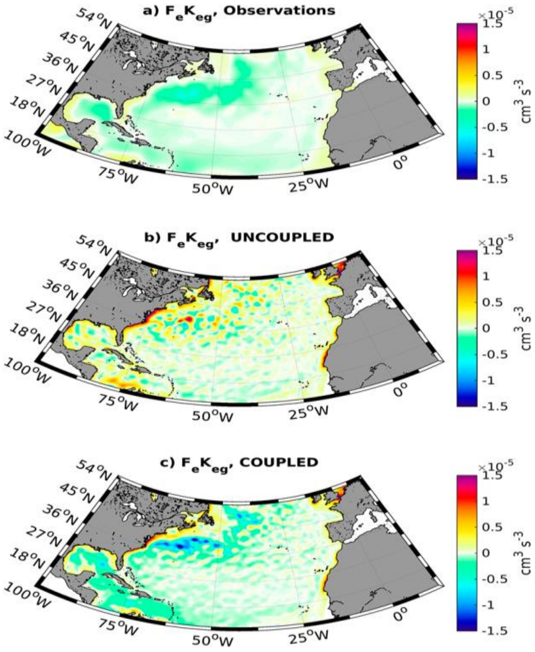
From Dickey (2003)

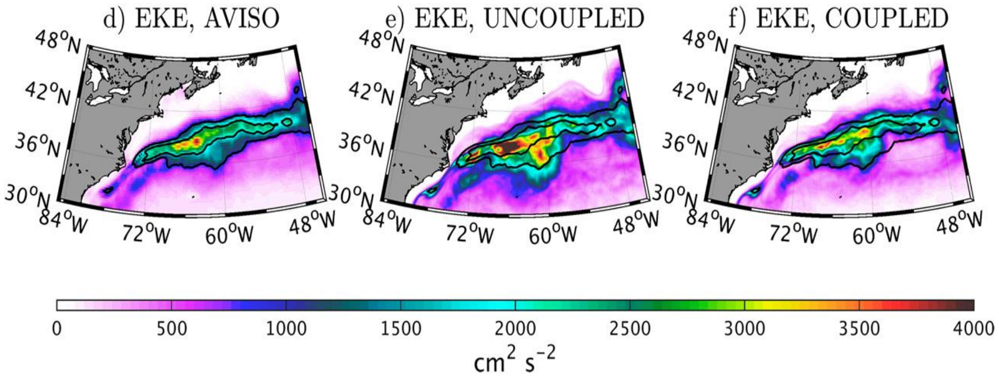
Impact of ocean current coupling on the ocean

- Coupling of surface currents to atmosphere feeds back on ocean circulation

$$\boldsymbol{\tau} = \rho_{\text{air}} C_D |\mathbf{U}|\mathbf{U},$$

$$\mathbf{U}_r = \mathbf{U}_a - \mathbf{U}_o,$$





Renault et al., 2016