Understand and Improving the Path of the Gulf Stream in Moderate Resolution Climate Models

End of First Year Report

Georgina Long
Supervisors: Prof. Beth Wingate & Dr. Mike Bell

May 2017

Hello.

1 Introduction

Ocean eddies are the subject of many ongoing investigations into ocean dynamics. The topic comprises a broad range of smaller-scale dynamics and relationships at varying scales. From energy transfer to blah blah *citations*, researchers are still trying to get a better understanding of the internal dynamics of the ocean. *citations*. Our main focus will be on the area of the Gulf Stream and mainly the interaction and effect of the bathymetry on the separation and subsequent path of the Gulf Stream.

The impact of an accurately resolved Gulf Stream The Gulf Stream is part of the AMOC and is essential to transferring heat from the Gulf of Mexico at lower latitudes towards western and northern Europe. Fundamentally it gives north-western Europe its mild climate and thus has large impacts on the weather as the heat is transferred into the atmosphere. This can have wide ranging effects on weather prediction such as winter blocking (Scaife *et al.*, 2011) *other citations and weather impacts* I'm sure I read about cyclones somewhere - find citation. Variations in the Gulf Stream have also been linked to flooding on the Eastern U.S. coast caused by the increase in sea surface level by (Ezer, 2015) among others.

It has been identified that the Gulf Stream has evolved over time, with (Greatbatch, Fanning, and Goulding, 1991) identifying a weakening of 30Sv between data from 1955-59 and 1970-74. Include about shutting down of GS in past. The dependence on the Gulf Stream for weather gives greater importance to our understanding and ability to predict the changes in the Gulf Stream. . Many lower resolution models render an unrealistic Gulf Stream, with the separation from the U.S. coast too far to the South, causing an inaccurate path from this point onwards. This causes knock-on effects as

Include Gulf Stream dimensions - or maybe mention if talking about scaling at some point?

Haven't added citations

Check this snentence

the corresponding sea surface temperatures (SSTs) are highter/lower than observed in the surrounding areas (Greatbatch *et al.*, 2004), and the continuing path of the Gulf Stream is innaccurate from the earlier misrepresentation. Given the importance of climate change and research into global warming, accurate representations of SSTs are vital for realistic predictions of the planets climate. Among the many processes at play are two gyres, the subpolar Norther Recirculation Gyre (NRG)which lies to the North of the Gulf Stream, and the subtropical Worthington gyre to the south of the Gulf Stream. These two gyres contribute to the transport of the Gulf Stream (Hogg *et al.*, 1986), and can be seen to weaken, strengthen or be displaced in response to changing dynamics in many of the models used to investigate the Gulf Stream and it's related dynamics as in (Greatbatch, Fanning, and Goulding, 1991) and (Zhang and Vallis, 2007) among others.

> **Do I need caps for this?**

The most common misrepresentation seems to be a separation from the coast to far south NEEDS a citation. This results in a cold bias in the north west corner of the Atlantic which has become known to modellers as the "blue spot of death" (Gnanadesikan, Griffies, and Samuels, 2007). Add figure? Lead into this a bit better - set up the link to the NRG and explain what it is? or leave this bit to later on The Northern Recirculation Gyre (NRG) interacts with the Gulf Stream and it has been noted by (Zhang and Vallis, 2007) and (Ezer, 2016)check this citation that the representation of the Gulf Stream can have large effects on the energy modelled within the NRG& the subtropical gyre too?. A lethargic NRG subsequently affects the *blah* find out about this and hence we can see that a poorly resolved Gulf Stream can have much wider implications throughout the model.

> **Not sure about this sentence**

> **interaction between the two rather than one to the other**

Problems and Restrictions   Higher resolution models have been shown to provide a more realistic Gulf Stream path citations. However this comes at a cost requiring more processing power and thus a more expensive model. It is understood citations (Nikurashin, Vallis, and Adcroft, 2012) etc. that this improvement is due to the higher resolution models being able to resolve small-scale processes which are lost in the coarser resolution counterparts. This is discussed further in section blah. (Ezer, 2016) suggests that to replicate an accurate Gulf Stream separation, the model not only needed to resolve the Gulf stream but also the northern branches of NRG, the southward slope and shelf currents. Could the bathymetry cause an unresolved northern branches of NRG?. citation It is also thought that the lack of detailed representation of the bathymetry in key areas play a large role in the unrealistic Gulf Stream path. citation posed that it is the interaction with the bathymetry and the consequential small-scale processes which cause the Gulf Stream to split off from the coast at Cape Hatteras and direct it's path from there. The bathymetry itself can be represented in many different ways and the vertical coordinate system chosen has a large impact on the interaction of the ocean dynamics and the ocean floor. This is discussed in more detail in section *blah*. Maybe add in here about scales - the different vertical levels and horizontal scales against the dimensions of the Gulf Stream?? *find citations* The Gulf Stream is 100km wide and varies from a depth of 800-1200km. Coarser models of 1°resolve to 100km per cell while 0.25°models resolve 25km per cell. These scales compared to the 100km width

> **Remove this?**

of the Gulf Stream demonstrate that a higher resolution model should give a clearer representation. This is akin to trying to identify a pixelated image - the higher the resolution, the clearer the picture.

TODO List

- Include size and scale of GS (some details in Mike's paper) - also can mention about resolution - e.g. if it's clear it isn't resolved in 1°models or something!

- Maybe include this in talk about it's evolution

- Mention that it stopped etc.

- (Scaife *et al.*, 2011) showed with their ocean only simulations that the SST bias off Newfoundland is significantly alleviated by increasing the horizontal resolution (from 1°to 0.25°) (End of section 4) - maybe include in Background too. The atmosphere only model provided mean bias and blocking error greatly alleviated at*both*resolutions.

2 Background

Tell a story up to where we are and what's missing.

Literature Review (take most from coursework).Cover the various angles including:

- Turbulence and bathymetry - understanding the smaller processes (vorticity etc.) (Tansley and Marshall, 2001) (Nikurashin, Vallis, and Adcroft, 2012)

- Inclulde some phenomenology - e.g. bottom vortex stretching and bottom pressure torque. Maybe also the weird sandwhich diagram!

- Include context of climate modelling (e.g. Scaife et al, Ezer summary etc)

- context of what affects the Gulf Stream etc.

- Possible relationships/data sets to see the history of the Gulf Stream. (Palaeo?) (Ezer, 2015)

- Cut down lit review - parts of it will be elsewhere!! (or should be! OR Remove them from elsewhere to keep them here!!)

- When introducing equations... maybe start with the basic equations then the vector invariant form of the momentum equation etc...????

- Modelling & vertical grid systems - include partial cells

- Balance between acceleration by wind stress and decelleration by pressure force on bottom topography (Naveira Garabato *et al.*, 2013) - he cites Vallis 2006 (Geoff's book!)??

Do I need to introduce the background? Do I have it as a lit review? Or Split it into separate topics within my thingy???? WAAAAAAAAAAAH

2.1 Gulf Stream Separation & NAC

- Maybe lead in through the Gulf Stream intro?

- Frame it in ocean eddies etc and energy transfer?

The Gulf stream separates at Cape Hatteras, skirts the Grand Banks at Newfoundland and then heads Eastwards towards western Europe. However, in many moderate resolution climate models this separation occurs further north than observed and turns more sharply to the East, as noted in (Hurlburt and Hogan, 2008) and often misses off the Grand Banks, heading straight towards Europe. This can lead to what modellers refer to as the "blue spot of death" (Gnanadesikan, Griffies, and Samuels, 2007), a patch of colder than observed SSTs resulting from the lack of heat at Newfoundland normally brought up by the Gulf Stream.

The exact cause for the path of the Gulf Stream is unknown, though it has been a research topic for many years and is still a popular topic amongst researchers today. A recurring theme when looking into the separation of the Gulf Stream is the mention of bathymetry. It is thought (Gula, Molemaker, and McWilliams, 2014)(Naveira Garabato *et al.*, 2013)(Nikurashin, Vallis, and Adcroft, 2012) that the ocean dynamics resulting from the interaction of the Gulf Stream and the deep western boundary current (DWBC) with the bathymetry in the North Atlantic could cause the turbulence required to direct the Gulf Stream along its path. A sudden change in the direction of the Gulf Stream just off the coast at South Carolina and Georgia has been attributed to the Charleston Bump, a topographical feature which raises the ocean floor, from a depth of 600m on the surrounding Blake Plateua to 200m (Gula, Molemaker, and McWilliams, 2014). Hence it is clear that bathymetry can strongly impact the direction of ocean currents.

2.2 Subpolar Gyre & subtropical gyre?

2.3 The Effects of topography

- Maybe introduct Streamfunction?

- Include Bottom Pressure Torque

- Include JEBAR

- Include Vortex Stretching etc. (Zhang and Vallis, 2007)

- (?)

- Bottom Pressure Torque to JEBAR. JEBAR is part of bottom pressure torque (see Geoff's book & (Greatbatch, Fanning, and Goulding, 1991)). The additional term corresponds to the torque of the vertically averaged pressure ((Greatbatch, Fanning, and Goulding, 1991))

The horizontal components of the vector invariant form of the momentum equation are: (From Geoff's book P64)

$$\frac{\partial u}{\partial t} - (f + \zeta)v + w\frac{\partial u}{\partial z} = -\frac{1}{a cos\phi}(\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + \frac{1}{2}\frac{\partial \mathbf{u}^2}{\partial \lambda}) \tag{1}$$

and

$$\frac{\partial v}{\partial t} - (f + \zeta)u + w\frac{\partial v}{\partial z} = -\frac{1}{a}(\frac{1}{\rho}\frac{\partial p}{\partial \phi} + \frac{1}{2}\frac{\partial \mathbf{u}^2}{\partial \phi}) \tag{2}$$

We start with the primitive horizontal momentum equations in spherical coordinates:
Primitive: 3 approximations: (From Geoff's book)

- The hydrostatic approximation. In the vertical momentum equation the gravitational term is assumed to be balanced by the pressure gradient term, so that

$$\frac{\partial p}{\partial z} = -\rho g \tag{3}$$

The advection of vertical veloicyt, the coriolis terms and the metric term $\frac{(u^2+v^2)}{r}$ are all neglected.

- The shallow-fluid approximation. We write $r = a + z$ where the constant a is the radius of hte Earth and z increases in the radial direction. The coordinate r is hten replaced by a except where it is used as the differentiating argument. Thus, for example,

$$\frac{1}{r^2}\frac{\partial(r^2 w)}{\partial r} \rightarrow \frac{\partial w}{\partial z} \tag{4}$$

- The traditional approximation. Coriolis terms in the horizontal momentum equations involving the vertical velocity, and the still smaller metric terms uw/r and vw/r, are neglected.

Then the governing equations become:

$$\frac{\partial u}{\partial t} = -((\mathbf{u}.\nabla)u - \frac{uv \tan\phi}{a}) + fv - \frac{1}{\rho_0 a \cos\phi}\frac{\partial p}{\partial \lambda} + \frac{1}{\rho_0}\frac{\partial \tau_\lambda}{\partial z} + F_\lambda \tag{5}$$

$$\frac{\partial v}{\partial t} = -((\mathbf{u}.\nabla)v + \frac{u^2 \tan\phi}{a}) - fu - \frac{1}{\rho_0 a}\frac{\partial p}{\partial \phi} + \frac{1}{\rho_0}\frac{\partial \tau_\phi}{\partial z} + F_\phi \tag{6}$$

Find a way to label the terms as nonlinear advection, coriolis acceleration, pressure gradient force, vertical diffusion of momentum, and horizontal diffusion of momentum.Maybe find an eqn with the 7 terms I'm using instead!?! have found the 7 terms in nemo - maybe work with this for now and come back to it later.

Make sure to define ϕ as going from the equator!!! and λ as the azimuth

Bottom Pressure Torque

JUST NOTES (Greatbatch, Fanning, and Goulding, 1991) Fig 1 & Fig 5 differences show the effect of bottom pressure torque missing from models which assume a flat bottom. They then have equations to demonstrate ((16) & (17)). (Greatbatch, Fanning, and Goulding, 1991) say bpt forcing responsible for enhacnign max transport of the subtropical gyre which combined with significant bpt forcing to the SE of the Grand Banks is important for determining the max trasnport of the diagnosed gulf stram.

See notes on Greatbatch paper in Papers doc for eqns - rewrite these in more modern notation - maybe consult Geoff's book! (**?**) "The relationship between JEBAR and BPT has been clarified by, among others, Mertz and Wright (1992), Greatbatch et al. (1991), and Bell (1999); the former arises in the (potential) vorticity equation of the vertically averaged horizontal flow, whereas the latter arises in the vorticity equation of the vertically integrated horizontal flow (see appendixA). JEBAR represents the component of BPT associated with the baroclinic (buoyancy de- pendent) part of the pressure gradient, and therefore it vanishes in the absence of stratification (Mertz andWright 1992; Salmon 1998). BPT can be nonzero regardless of stratification because it represents the projection of hori- zontal geostrophic bottom flow normal to isobaths. With the condition of no normal flowat the ocean bottom,BPT can be understood as a geostrophic bottom vortex stretching" (See eq (1) in paper).

We start with the blah blah of the momentum equation,

$$ \tag{7} $$

JEBAR

JUST NOTES (Greatbatch, Fanning, and Goulding, 1991) JEBAR accounts for part of the bottom pressure torque - Greatbatch has a good example of difference between solutions where JEBAR is 0 and other part is 0 to show the significance of JEBAR term.

Then JEBAR itself can be split into separate parst - see (Greatbatch, Fanning, and Goulding, 1991) and (Gula, Molemaker, and McWilliams, 2014).

See notes on Greatbatch paper in Papers doc for eqns - rewrite these in more modern notation - maybe consult Geoff's book!

The Joine Effect of Baroclinicity And Relief (JEBAR) was first introduced to account for the effects of topography and baroclinicity in ocean dynamics. It is these effects which balance with the wind stress. This is terrible writing oh my god what areyou doing. just write something half way decent. In fact just write anything. Find an equation to write down to explain what JEBAR is.

Bototm Vortex Stretching

2.4 Small Scale Processes

- Lots from lit review - and add some dissipation stuff.

It has been noted that in higher resolution models, the separation and subsequent path of the Gulf Stream is much more accurate than in the lower resolution counterparts (Hurlburt and Hogan, 2008)(Zhang and Vallis, 2007). This lends to the idea that the processes which affect the Gulf Stream occur on smaller scales which aren't resolved by coarser models (Naveira Garabato *et al.*, 2013)(Nikurashin, Vallis, and Adcroft, 2012). Various processes have been investigated and suggested as the main influences though it is likely that the improved Gulf Stream representation is due to multiple factors.

(Naveira Garabato *et al.*, 2013) theorised that interaction with the bathymetry creates small-scale turbulence and instabilities which could cause bathymetric steering and divert currents. If this is not being represented in coarser models, the energy behind the turbulence must be going elsewhere. (Scott *et al.*, 2010) compared current meter readings with modelled values for kinetic energy and noticed that in some areas of the North Atlantic the total kinetic energy was being held higher in models than observed. It is discrepancies such as this which could have much wider implications. If the energy is not penetrating to the ocean floor, we cannot expect to be able to replicate the effects of the bathymetry. Perhaps by pulling this energy further down (closer to observed values), there would be more energy transfer from the larger ocean eddies to the smaller scale turbulence resulting from interaction with the bathymetry.

(Tansley and Marshall, 2001) used a simplified model of water flowing past a cylinder to highlight the importance of turbulence on fluid motion. Using a quarter-cylinder (mimicking a simplified version of Cape Hatteras) and a high Reynolds number (allowing for more turbulent flow), the model produced a jet with surrounding turbulent eddies similar to those observed in the Gulf Stream. These results were not seen with a lower Reynolds number, highlighting the importance of turbulence in forming jets like the Gulf Stream.

The turbulent mixing arising from interaction with the bathymetry could allow geostrophic eddies to transfer some of their energy to smaller processes by causing internal waves to break and contribute to enhanced mixing (Nikurashin, Vallis, and Adcroft, 2012). These effects have been seen even in cases of small-scale bathymetric roughness suggesting that it is not necessary to have large topological features to impact ocean dynamics, instead small surface differences can cause changes which lead to bigger outcomes.

(Naveira Garabato *et al.*, 2013) attribute the significant impact of small-scale bathymetry to wave drag. Although wave drag is not a large contributor to ocean dynamics, topological features on a small scales can cause wave drag which contributes ten to several tens of a percentage of the dominant source and sink terms influencing the vorticity of the ocean.

These effects of small-scale processes are not limited to the Gulf Stream, but impact on many aspects of ocean dynamics as the various currents and features affect one another. (**?**) speculated that amongst other things, the northern branches of the Northern Recirculation Gyre (NRG) would have to be resolved in order to produce an accurate Gulf Stream in a model. (Zhang and Vallis, 2007) determined that a significant contribution to the generation of the NRG is the bottom vortex stretching resulting from

a downslope DWBC, which is in turn the result of the interaction with bathymetry as the DWBC crosses the path of the Gulf Stream. Hence, bathymetric impact can circle around to affect many aspects of ocean dynamics.

2.5 Energy Dissipation

- How the energy is changed from global eddies to smaller spin and/or lost. internal wave drag etc?

2.6 Climate Models

- Talk about model resolution and improvements

- Mention Zanna paper???

- Different vertical coordinate systems

- Effects of the Gulf Stream in models etc. Scaife et al...

- Parameterisations and improvements etc. Work being done on the more modelly side!

Modelling the Gulf Stream As more scientsts seek to understand ocean dynamics, more models are made and used by different researchers to simulate different processes. There are many models in use today, all with different configurations and settings. This can lead to contrasting outcomes and debate over which choice of model or model settings yields the most accurate results.

Model Resolution

A long with differing numerical schemes or boundary conditions, etc. there are also many different model resolutions available. These range from coarse 1° models, which resolve to a scale of $\approx$ 100km, to higher resolution 0.25° models, which resolve to a scale of $\approx$ 25km, all with varying numbers of vertical levels. It is well established (Scaife *et al.*, 2011)(Hurlburt and Hogan, 2008) that a higher resolution ocean model tends to produce a more accurately resolved Gulf Stream. This is in part due to the small scale processes, mentioned previously, which contribute to the ocean circulation, but are not resolved in the coarser models. Unfortunately higher resolution models require additional processing power and thus additional costs. This means that the high resolutions required to resolve a realistic Gulf Stream will not be widely used for some time. Hence, the aim is to find a way to represent an accurate Gulf Stream in the lower resolution models by understanding the reasons behind it.

Vertical Coordinate System

O ne of the main variabilities between different models is the handling of the vertical coordinate system. The way in which the model splits the depth of the ocean into 'levels' can have a large impact on the way the bathymetry is represented. As previously discussed, this bathymetric representation can have large impacts on the dynamics within the model. The importance and significance of the bathymetric roughness has already been discussed in this review so it is now necessary to discuss the different ways to represent this.

T he main coordinate systems in use are the z-coordinate system which stays true to a cartesian system of coordinates, consisting of rectangular 'blocks', which create a staircase effect when representing slopes. These z-coordinate systems can also be implemented with 'partial cells' whereby some of the cells are cut into smaller cells to 'smooth out' and more closely represent the shape of the slopes. Thre are also s- (or sigma-) coordinates which follow the shape of the terrain. The depth at any point is divided by the number of levels to create a consistent number of cells at all points of different thickness. These different approaches can also be combined to form hybrid coordinate systems. See Figure 1 for an illustration of some of the possible vertical coordinate systems available in the NEMO model.

T he main difficulty in comparing different vertical coordinate systems lies in the availability of a 'control' case for the comparison. With the wide selection of models available to researchers, it is not only the vertical coordinate system which differs but also the numerical schemes being used to resolve various processes. This could lead to false similarities or differences and cause incorrect conclusions. (**?**) was able to compare results from z-coordinate models and s-coordinate models while minimalising any other differnces between the models. Although the z-coordinate models are capable of producing an accurate Gulf Stream at hight resolutions, the s-coordinate models provided a more accurate representation when restricted with coarser models. However, as (**?**) noted in the comparison, partial and shaved cells (whereby corners of the cells are 'shaved' off to smooth out slopes) were not used in any of these models.

3 Barotropic Vorticity Diagnostics

Results so far - link into Background & lead nicely into the next section.

3.1 Barotropic vorticity diagnostics

- Results so far

- Discussion on results and possible implications

- Results on what we're looking at and why

- Maybe brief description of JEBAR etc. to explain it's use & who else has used it to show what - e.g. why are we looking at it etc?
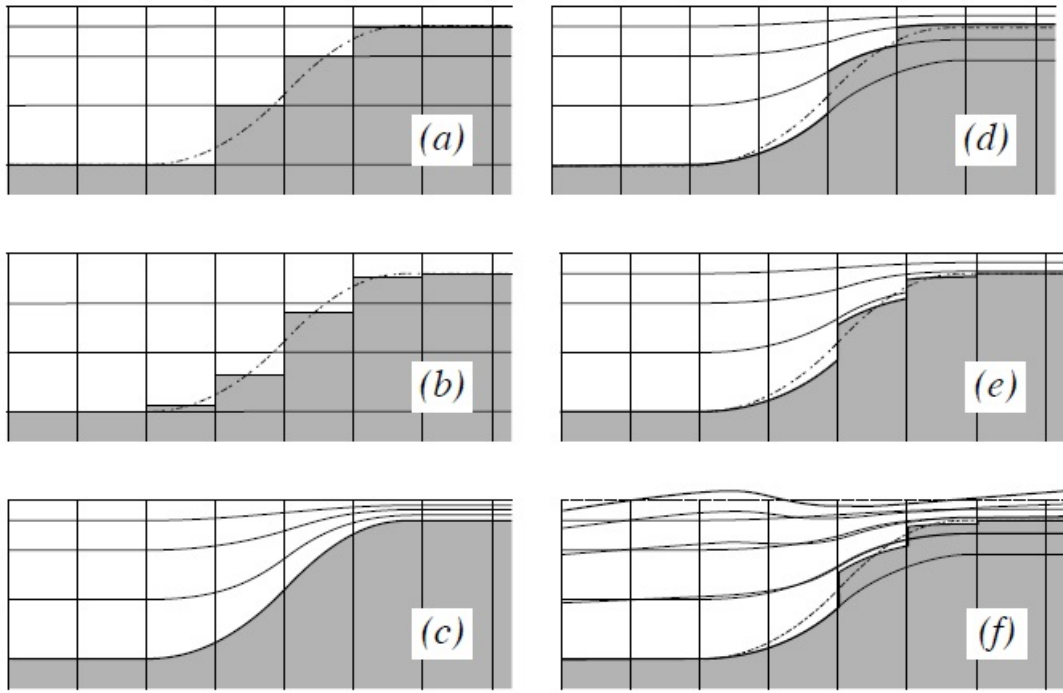
Figure 1: An illustration of different veritcal coordinate systems available in NEMO. (Madec, 2011). (a) z-coordinate, (b) z-coordinate with partial cells, (c) s-coordinate, (d) hybrid s-z coordinate, (e) hybrid s-z coordinate with partial cell, (f) shows (e) with a non-linear free surface (which can be used with any coordinate system).

- Should probably include model set up

Blhablha don't know how to start this section lalala! Using the NEMO model, we are in the process of including some barotropic vorticity diagnostics to further investigate the processes effecting the path of the Gulf Stream. These barotropic vorticity diagnostics have been used by (**?**),(**?**) and other people to examine who knows what. The momentum equations in the model are momentum equations and terms. Two diagnositcs will be calculated on each of the XX terms. Better wording from Mike's paper: the curl can be taken of the terms in the vertical average/integral of the momentum equations. Integrate over depth. For each contribution to the momentum equations, we will first calculate the vertical integrals, $\bar{u}$ and $\bar{v}$, over the height of the water column from the depth, $-h$, to the sea surface level η,

$$\bar{u} = \int_{-h}^{\eta} u dz, \qquad \bar{v} = \int_{-h}^{\eta} v dz \qquad (8)$$

We will also calculate the vertical averages $\langle \bar{u} \rangle$ and $\langle \bar{v} \rangle$ over the height of the water column,

$$\langle \bar{u} \rangle = \frac{1}{\eta + h} \int_{-h}^{\eta} u dz, \qquad \langle \bar{v} \rangle = \frac{1}{\eta + h} \int_{-h}^{\eta} v dz \qquad (9)$$

The first diagnostic will be obtained by taking the vertical component of the curl. EQUA-TION

$$BVI(a) = \frac{\partial \bar{v}}{\partial x} - \frac{\partial \bar{u}}{\partial y} \qquad (10)$$

check this

The second diagnostic is obtained by taking the vertical average of the momentum contribution over the depth H of th ocean and then taking the vertical component of the curl.

$$BVA(a) = \frac{\partial \langle \bar{v} \rangle}{\partial x} - \frac{\partial \langle \bar{u} \rangle}{\partial y} \qquad (11)$$

check this

find a better wording of this!

Using these diagnostics, we can calculate the barotropic and lots of other things streamfunction which will help to pinpoint blahblahblah. Go into each of the contributing factors - put the equation maybe? or at least pick them out from above - look at Mike's paper for help!!

find out what!!

ln_zps=true : z-coordinate with partial step bathymetry

Prognostic Ocean dynamics equations summarised as:

$$NXT = (VOR + KEG + ZAD) + HPG + SPG + LDF + ZDF \qquad (12)$$

$(VOR + KEG + ZAD)$ are the coriolis & advection terms. Then the prsesure gradient contributions (HPG - hydrostatic & SPG - surface pressure), LDF - lateral diffusion & ZDF - vertical diffusion (Madec, 2011) P102

3.2   Bottom Pressure Torque

3.3   Vortex Stretching

4   Future Aims/Questions/Lines of Enquiry update title!

We seek a robust & accurate Gulf Stream path. How can we improve the representation & thus understanding of the Gulf Stream?

We seek to improve the understanding and representation of the Gulf Stream in moderate resolution models. As we have discussed, there are many processes involved in the dynamics of the ocean and thus there are many different directions to turn to when seeking solutions to this problem. Here we will focus on the interactions and effects of the bathymetry while being careful not to ignore other paths this investigation may lead down.

> Merge with next section

4.1   Identifying key processes

- Understanding

- Representation

It is speculated *paper*that interaction with the bathymetry creates small-scale turbulence and instabilities which can cause bathymetric steering and divert currents. If this is not being represented in coarser models, the energy behind the turbulence must be going elsewhere. *paper* compared simulated kinetic energy over different models against measurements taken and noted that in some areas the total kinetic energy was being held higher in the ocean in the models than observed. It is discrepancies such as this which could have much wider implications. If the energy is not penetrating to the ocean floor, we cannot expect to be able to replicate the effects of the bathymetry. Perhaps pulling this energy further down (closer to observed values), we would be able to see the energy transfer from *** to the turbulence resulting from the bathymetry.

> female author?

> paper

> choose a different word

> ?

Of course as previously discussed there are many processes which could contribute to a Gulf Stream path staying too far South. (Ezer, 2016) speculated that amongst other things, the northern branches of the NRG would have to be resolved in order to produce an accurate Gulf Stream. (Zhang and Vallis, 2007) determined that a significant contribution to the generation of the NRG is the bottom vortex stretching resulting from a downslope DWBC, which is in turn the result of the interaction with the bathymetry as the DWBC crosses the path of the Gulf Stream. Thus we see that this circles back to interaction with the bathymetry.

4.2   Different model formulations

- Representation of the bathymetry

- Effects of different vertical grids

12

The many different ocean and OGCM models available allow us to see the effects of many different schemes and parameterisations in use today. In particular the choice of vertical coordinate system has long been discussed, especially in regard to its relevance here. Obviously the representation of the topography and the way it is rendered in the model is a result of the vertical coordinate choice. (Ezer, 2016) revisited the discussion in relation to the Gulf Stream separation and used similar models to determine the most accurate results over different choices for coordinate systems. However, the z-coordinate system chosen did not include any partial or shaved cells. It is inherently obvious that using the z-coordinate system would cause the various slopes in the ocean floor to appear as steps which would significantly alter the flow around the area. . It is not so surprising perhaps that under these circumstances (Ezer, 2016) found sigma or s-coordinates to be the most realistic given that they allow for a smooth ocean floor. It is perhaps natural then to question the effect of partial or shaved cells on these findings. As NEMO allows for such a diverse range of configurations and schemes, it would be interesting to recreate these results while implementing a z-coordinate system with partial cells to allow for a new take on this review.

> A diagram of the different coordinate systems?

> Maybe move to the next section instead?

4.3   Gulf Stream interaction with other systems

- Interaction with other currents (DWBC, etc.)

- Relationship with data sets

- Evolution of the Gulf Stream

5   Lines of Enquiry & Methodology

5.1   NEMO

- Model Resolution (Ezer, 2016)

    - simple configurations? (Tansley and Marshall, 2001)

- Representation of Bathymetry

    - Vertical Coordinate Systems
    - Partial Cells
    - Nested grids (enhancing resolution in specific areas?)

To examine the aforementioned interplay between the NRG and the path of the Gulf Stream, a simple configuration of NEMO simulating the double gyre set-up seen by the NRG north of the Gulf Stream and the subropical(?) gyre south of the gulf stream could be used to examine the effects in an idealised model. Results from this could help to influence our investigations within the more realistic models. As (Tansley and Marshall,

> Diagnostics across different model resolutions and schemes

> Can't think of the other thing that was in my head earlier

2001) used the classic problem of flow past a cylinder to understand the Gulf Stream separation, we too can learn from idealised set up and by breaking the problem down to its fundamental aspects.

5.2 Understanding the Gulf Stream

- Turbulence (&Geostrophic turbulence)

- Vorticity and it's contributors

It has been discussed previously that a lack of energy transfer, either by lack of interaction with the bathymetry, or via some other process, could be to blame for the low levels of turbulence found in the area surrounding the separation of the Gulf Stream. As seen when (Tansley and Marshall, 2001) used a larger Reynolds number, allowing for more turbulent flow, flow passing a quarter-cylinder (akin to the coastline at Cape Hatteras), formed jet like streams with smaller eddies breaking away from it. This is akin to satellite observations of the Gulf Stream . This leads to the question which many try to answer how can we improve/enhance the turbulence in a model?

> here? Or do I need to recite?

> could I put a side by side of the two pictures here? Satellite v Tansley/Marshall picture?

5.3 Gulf Stream Relationships

- Data Sets (Ezer, 2015)

    - Explore the possible links between the Gulf Stream and other data sets (e.g. coastal sea level)

- Impact of other currents (Ezer, 2015)

- Changes in the Gulf Stream (Greatbatch, Fanning, and Goulding, 1991) (Ezer, 2015)

Notes

- Make lit review more specific - focus it on a few key papers rather than covering a ton of them!

- Focus on phenomenology rather than model stuff

- Add a section somewhere to explain bottom pressure torque and bottom vortex stretching - maybe in diagnostics secion but elsewhere too

- Maybe add in weird sandwhich scales phenomenology?

- Explain vertically integrated blah blah

- Find out a use for the vertical average info.

- Maybe discuss Sverdrup vs barotropic streamfunction transport? (see P2075 bottom right blue highlighted in Vallis & Zhang 2007)

- Include how the energy is dissipated and where it goes when it hits the bottom - I think this was John T's q from my talk

- PHENOMENOLOGY

- What am I doing with the average?

References

Ezer, T.: 2015, Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009-2010 and estimated variations for 1935-2012. *Global and Planetary Change* **129**, $23-36$. doi:10.1016/j.gloplacha.2015.03.002. http://dx.doi.org/10.1016/j.gloplacha.2015.03.002.

Ezer, T.: 2016, Revisiting the problem of the Gulf Stream separation: On the representation of topography in ocean models with different types of vertical grids. *Ocean Modelling* **104**, $15-27$. doi:10.1016/j.ocemod.2016.05.008.

Gnanadesikan, A., Griffies, S.M., Samuels, B.L.: 2007, Effects in a climate model of slope tapering in neutral physics schemes. *Ocean Modelling* **16**(1-2), $1-16$. ISBN 1463-5003. doi:10.1016/j.ocemod.2006.06.004.

Greatbatch, R.J., Fanning, A.F., Goulding, A.D.: 1991, A Diagnosis of Interpentadal Circulation Changes in the North Atlantic. *JOURNAL OF GEOPHYSICAL RESEARCH* **96023**(15), $9-22$. doi:10.1029/91JC02423.

Greatbatch, R.J., Sheng, J., Eden, C., Tang, L., Zhai, X., Zhao, J.: 2004, The semi-prognostic method. *Continental Shelf Research* **24**(18), $2149-2165$. doi:10.1016/j.csr.2004.07.009.

Gula, J., Molemaker, M.J., McWilliams, J.C.: 2014, Gulf Stream Dynamics along the Southeastern U.S. Seaboard. *Journal of Physical Oceanography* **45**(3), $690-715$. doi:10.1175/JPO-D-14-0154.1. http://journals.ametsoc.org/doi/abs/10.1175/JPO-D-14-0154.1%5Cnhttp://journals.ametsoc.org/doi/pdf/10.1175/JPO-D-14-0154.1.

Hogg, N.G., Pickart, R.S., Hendry, R.M., Smethie, W.J.: 1986, The northern recirculation gyre of the gulf Stream. *Deep Sea Research Part A, Oceanographic Research Papers* **33**(9), $1139-1165$. doi:10.1016/0198-0149(86)90017-8.

Hurlburt H.E., Hogan P.J.: 2008, The Gulf Stream pathway and the impacts of the eddy-driven abyssal circulation and the Deep Western Boundary Current. Dynamics of Atmospheres and Oceans. ISBN 0377-0265. doi:10.1016/j.dynatmoce.2008.06.002.

Madec G.: 2011, NEMO Ocean Engine, 1−332. `http://www.nemo-ocean.eu/About-NEMO/Reference-manuals{%}5Cnpapers2://publication/uuid/73E7FF17-99BE-4B10-A823-0037C823EF6E`.

Naveira Garabato, A.C., Nurser, A.J.G., Scott, R.B., Goff, J.A.: 2013, The Impact of Small-Scale Topography on the Dynamical Balance of the Ocean. *Journal of Physical Oceanography* **43**(3), 647−668. doi:10.1175/JPO-D-12-056.1. http://journals.ametsoc.org/doi/abs/10.1175/JPO-D-12-056.1.

Nikurashin, M., Vallis, G.K., Adcroft, A.: 2012, Routes to energy dissipation for geostrophic flows in the Southern Ocean. *Nature Geoscience* **6**(1), 48−51. ISBN 1752-0894. doi:10.1038/ngeo1657. http://www.nature.com/doifinder/10.1038/ngeo1657.

Scaife A.A., Copsey D., Gordon C., Harris C., Hinton T., Keeley S., O'Neill A., Roberts M., Williams K.: 2011, Improved Atlantic winter blocking in a climate model. Geophysical Research Letters. ISBN 0094-8276. doi:10.1029/2011GL049573. `http://0-onlinelibrary.wiley.com.lib.exeter.ac.uk/doi/10.1029/2011GL049573/epdf`.

Scott, R.B., Arbic, B.K., Chassignet, E.P., Coward, A.C., Maltrud, M., Merry-field, W.J., Srinivasan, A., Varghese, A.: 2010, Total kinetic energy in four global eddying ocean circulation models and over 5000 current meter records. *Ocean Modelling* **32**(3-4), 157−169. ISBN 1463-5003. doi:10.1016/j.ocemod.2010.01.005. http://dx.doi.org/10.1016/j.ocemod.2010.01.005.

Tansley, C.E., Marshall, D.P.: 2001, Flow past a Cylinder on ab Plane, with Application to Gulf Stream Separation and the Antarctic Circumpolar Current. *Journal of Physical Oceanography* **31**, 3274−3284. doi:10.1175/1520-0485(2001)031¡3274:FPACOA¿2.0.CO;2.

Zhang, R., Vallis, G.K.: 2007, The Role of Bottom Vortex Stretching on the Path of the North Atlantic Western Boundary Current and on the Northern Recirculation Gyre. *Journal of Physical Oceanography* **37**, 2053−2080. doi:10.1175/JPO3102.1.