Paper summaries and notes

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1 (Scaife *et al.*, 2011)

(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 Intro & Background too. The atmosphere only model provided mean bias and blocking error greatly alleviated at *both* resolutions.

- Shows importance of a resolved North Atlantic Current.
- Mentions the SST bias off Newfoundland.
- Uses NEMO 1°and 0.25°models.
- Same number of vertical levels in both.
- Highlights importance of accurate SSTs. Atlantic SSTs can affect surface baroclinicity, thermal winds and baroclinic eddy growth.

2 Greatbatch1991

(Greatbatch, Fanning, and Goulding, 1991)

- Importance of JEBAR (mentioned in Section 3)
- GS transport decreases for 80Sv to 50Sv from 1955-1959 to 1970-1974
- Transport stream function for climatological mean state with JEBAR set to 0 is very different. Transport stream function for climatological mean state with WIND set to 0 is very similar. Implies that JEBAR give significant contribution.
- 1°model solving for streamfunction.
- Equations showing BPT & sverdrup relation in section 4

- "It is also apparent that there is significant bottom pressure torque forcing to the south-east of the Gand Banks of Newfoundland and that this, together with that enhancing the transport of the subtropical gyre, is important for determining the maximum transport (80 Sv) of the diagnosed Gulf Stream. Indeed, it can be seen from Figure 6 that bottom pressure torque alone accounts for over 70Sv of this transport." (after eqn (21)).

- Figures 5 & 6 support the views from Wunsch and Roemich (1985) that transport in the North Atlantic driven by bottom pressure torque is likely of comparable magnitude to that driven by the surface wind stress curl. Similar magnitudes of Ψ_B and Ψ_S in figs 5 & 6 support this.

- Eqn(25) shows that the JEBAR differs from the bottom pressure torque by a term that is the corresponding torque associated with the vertically averaged pressure.

- Fig 1 & 5 differences show the effect of bottom pressure torque missing from modles which assume a flat bottom. Eqns also demonstrate (16) & (17) onwards. (though note fig 5 soln doesn't include the effect of friction - but friction only essential in palaces where $\frac{f}{H}$ contours terminate - pg6). See below for eqns.

- Splits the stream function into different parts.(By Eqn (21) & elsewhere) Ψ_S and Ψ_B with $\Psi_B = \Psi - \Psi_s$. Fig 6 shows Ψ_B the part of fig 1 driven by bottom pressure torque. BPT accounts for over 70Sv of GS transport alone.

- Can see that the effects of bpt can displace the subpolar gyre southward - big impact on British Isles.

Include this in intro? Links to importance

- P10 explains why JEBAR so important in NE Atlantic. Verift importance by overlaying contours of potential energy Φ and depth H. As $JEBAR = J(\Phi, \frac{1}{H})$ it will be nonzero in regions where these regions cross. The NE Atlantic is one such region.

- For subtropical gyre - bottom pressure torque effect more important than density compensation.

- Change between pentads due to JEBAR dominates that due to WIND. (Section 4)

- Change in bpt between pentads is responsible for the weaker subtropical gyre and the increased Ψ values along 41°N and 28°W latitude to the west. These two combined accound for a 45Sv transport reduction around 40°N - explaining the 35Sv reduction in the Gulf Stream.

- In subpolar gyre - bpt responsible for shiting the SE part Nward but no change in transport.

- When looking at changes to Φ above 1500m only - and calculating the Ψ due to these changes, it accounts for roughly half of the total Ψ and approx 24Sv transport in the Gulf Stream region.
- Transport of GS is 30Sv less for 70-74 than 55-59. 20Sv of this is due to a dramatic decrease in the strength of the subtropical gyre. This 20Sv is due to a change in bottom pressure torque forcing on the W side of the Mid-Atlantic Ridge (nr 35°N and 28°W). The remaining 10Sv is due to changes in bottom presure torque in the Eastern Atlantic (nr 41°N and 28°W). About half is due to changes in the density field in depe water below 1500m - this may be unreliable but the remaining half (above 1500m) is reliable & still significant.
- JEBAR split in two: a part associated with the bottom pressure torque & a part associated with the compensation by the density stratification for the effect of variable bottom topography. -¿ This leads to the split of the streamfunction (See below).
- JEBAR separation leads to Ψ split: $\Psi = \Psi_W + \Psi_C + \Psi_B$. Ψ_W - uniform density ocean. Ψ_C - driven by density compensation part of JEBAR. Ψ_B - driven by bottom pressure torque. $\Psi_S = \Psi_W + \Psi_C$ is the prediction of the flat-bottomed Sverdrup relation.
- subpolar gyre affected by Ψ_C and Ψ_B (with the latter extending the gyre southward rather than enhancing circulation).
- subtropical gyre afected by Ψ_W and Ψ_B (with the latter leading to enhanced gyre circulation).
- Nearly all changes between tthe two pentads is due to the bpt part of Ψ (Ψ_B).
- Calculation of Ψ_B depends on Ψ_S and thus on the quality o the surface wind stress fields.

Explanation of discrepancy between fig 1 & fig 5 That the flat bottom sverdrup relation shows the results of removing the bottom pressure torque.
Start with momentum equations:

$$-fv = -\frac{1}{a\rho_0 cos\phi}\frac{\partial p}{\partial \lambda} + \frac{1}{\rho}\frac{\partial \tau_(z\lambda)}{\partial z} \tag{1}$$

$$fu = -\frac{1}{a\rho_0}\frac{\partial p}{\partial \phi} + \frac{1}{\rho}\frac{\partial \tau_(z\phi)}{\partial z} \tag{2}$$

Vertivally integrate the momentum eqns. Assume bottom stress to be 0 (as when deriving (7) and (8)

$$-fV = -\frac{1}{a\rho_0 cos\phi}[\frac{\partial}{\partial \lambda}(\int_(-H)^0 pdz) - p_b H_\lambda] + \frac{\tau^s_\lambda}{\rho_0} \tag{3}$$

check why bottom stress is 0

$$fU = -\frac{1}{a\rho_0}[\frac{\partial}{\partial\phi}(\int_(-H)^0 pdz) - p_b H_\phi] + \frac{\tau^s_\phi}{\rho_0} \tag{4}$$

Now do $\frac{\partial 4}{\partial\lambda} = \frac{\partial cos\phi 3}{\partial\phi}$ and using:

$$\frac{1}{acos\phi}(\frac{\partial U}{\partial\lambda} + \frac{\partial}{\partial\phi}(Vcos\phi)) = 0 \tag{5}$$

and

$$aU = -\Psi_\phi quadaVcos\phi = \Psi_\lambda \tag{6}$$

we have:

$$(\frac{df}{d\phi}\Psi_\lambda = \frac{1}{\rho_0}J(p_b, H) + \frac{a}{\rho_0}[\frac{\partial}{\partial\lambda}(\tau^s_\phi) - \frac{\partial}{\partial\phi}(cos\phi\tau^s_\lambda)] \tag{7}$$

an alternative way to express 7 is:

$$\beta V = \frac{1}{\rho_0}[\hat{k}\dot{c}url(p_b\nabla H) + \hat{k}\dot{c}url(\tau^s)] \tag{8}$$

which makes it clear that the $J(p_b, H)$ term in 7 corresponds to the bottom pressure torque $\hat{k}\dot{c}url(p_b\nabla H)$. and if bpt everywhere is 0 7 becomes the flat-bottomed Sv relation used to obtain fig 5.

Show relationship between JEBAR and bottom pressure torque Integrate the hydrostatic relation1G

$$\frac{\partial p}{\partial z} = -\rho_0 b \tag{9}$$

to get

$$p = p_b - \rho_0 \int_(-H)^z bdz \tag{10}$$

and now integrate vertically to get:

$$H(\bar{p} - p_b) = -\rho_0 \int_(-H)^0 \int_(-H)^z bdz'dz \tag{11}$$

where $\bar{p} = \frac{1}{H}\int_(-H)^0 pdz$. Applying integration by parts to the RHS & using $\Phi = \int_(-H)^0 zbdz$, 11 can be written:

$$H(\bar{p} - p) = \rho_0\Phi \tag{12}$$

and so using $JEBAR = J(\Phi, \frac{1}{H})$ ((10) in paper) it follows:

$$JEBAR = \frac{1}{\rho_0 H}[J(p_b, H) - J(\bar{p}, H)] \tag{13}$$

Hence, JEBAR differs from bpt by a term corresponding to the torque associated with the vertically averaged pressure $\bar{p}$. (Remeber: $\bar{p} = \frac{1}{H}\int_(-H)^0 pdz$)

Splitting the Stream function Ψ can be split into two parts: Ψ_S calculated form the flat-bottomed Sverdrup relations and Ψ_B due to the bottom pressure torque. We can futher split Ψ_S into two parts: Ψ_W given by integrating

$$J(\Psi, \frac{f}{H}) = JEBAR + WIND \tag{14}$$

with $JEBAR = 0$ and Ψ_W=0 at the eastern boundary. This is the Ψ field for a uniform density ocean. See fig2a. $\Psi_C = \Psi_S - \Psi_W$ is then part of Ψ obtained by integrating 14 with $JEBAR = JEBAR_c$ ($JEBAR_c$ is a nonzero $JEBAR$ mentioned in the paper), $WIND = 0$ and $\Psi_C = 0$ at the Eastern boundary. It is the part of Ψ associated with compensation by the density stratification for the effect of bottom topography.
Total Ψ is $\Psi = \Psi_W + \Psi_C + \Psi_B$. $\Psi_B + \Psi_C$ is the part driven by JEBAR shown in fig2b. Thus $JEBAR$ can be split into two parts: a part associated with density compensation ($JEBAR_C$) and a part associated with bottom pressure torque ($JEBAR - JEBAR_C$). Each part can be obtained by differentiating the respective streamfunction (i.e. Ψ_B or Ψ_C along $\frac{f}{H}$ contours. NOTE: These two parts don't correspond to the two parts in 13.

3 Salmon

(?)

Chapter 13 The Effect of Bottom Topography

- Bottom Torque is the first term in the vorticity equation (13.12)

$$\beta \Psi_x = J(\phi_b, H) - \epsilon \nabla^2 \Psi + \nabla.(fH\bar{\mathbf{u_E}}) \tag{15}$$

  obtained by cross differentiating the vertical integral of the horizontal momentum equations.

- Bottom torque exists wherever the ocean bottom slopes and the bottom pressuer ϕ_b varies along isobaths. Note that:

$$J(\phi_b, H) = [J(\phi, H)]_b \tag{16}$$

  even though $[\nabla \phi]_b \neq \nabla(\phi_b)$. By the hydrostatic relation $\frac{\partial \phi}{\partial z} = \theta$ so we can write the vorticity eqn in a different way. (13.18) which splits the bottom torque over several terms.

- The second term in this represents the part of the bottom torque arising from the baroclinic (θ-dependent) part of the pressure. This vanishes if the fluid is homogenous or the ocean is flat ($H = 1$). This term is sometimes called the jebar term (Joint Effect of Baroclinicity And Relief).

$$JEBAR = J(\frac{1}{H}, \gamma) \tag{17}$$

  where $\gamma \equiv -\int_(-H)^0 z\theta dz$ and $J(A, B) \equiv \frac{\partial A}{\partial x}\frac{\partial B}{\partial y} - \frac{\partial A}{\partial y}\frac{\partial B}{\partial x}$ is the horizontal Jacobian operator.

- The jebar term couples the temperature field to the vertically averaged flow. In homogenous fluid ($\theta = 0$) jebar vanishes.

4 Gula2014

(Gula, Molemaker, and McWilliams, 2014)

- Good description of GS : passes through Strait of Florida then flows northward pressed against the confining wall of the southeastern U.S. continental shelf belfore leaving the slope at Cape Hatteras.
- GS path controlled by combination of boundary shape, bottom topography, entrainment of fluid from the gyre interior, and the adjustment of the flow tothe incrase in planetary vorticity as fluid is advected northward.
- cyclonic eddies propagate along the shelf (on the inshore side of the gulf Stream) - these are "frontal eddies" and occur where the Gulf Stream interacts with the slope and shelf. They're formed of deep, upwelled, cold domes.
- Eddies and meanders have strong implications for the biological production in the South Atlantic Bight (cites Lee et al. 1991) - important for biological reasons! (This is often one of the ways you can identify the Gulf Stream from Satellite images - e.g. ocean circulation book cover I think). check this
- Charleston bump disrupts the Gulf Stream, deflecting it further Eastward and generating large meanders. The pressure forces at the bump generate drags and torques likely to impact strongly the momentum and corticity balances of the stream (which remain to be quantified).
- Charleston bump - preferred region for eddy generation using satellite-based measurements and statistics.
- other papers (Hood and Bane 1983 & Dewar and Bane 1985) show both a large mean-to-eddy conversion at the bump and eddy-to-mean conversion downstream.
- mean-to-eddy conversion where the mean velocity gradient is the source for eddy generation through instability processes. Implies a down-gradient momentum transport and a deceleration of the mean flow.
- eddy-to-mean conversion more counterintuitive as it requires an upgradient momentum transport. The eddies are accelerating the mean flow.

- Xie et al 2007 conclude that the isobathic curvature plays a role in enhancing the baroclinic and barotropic energy conversion, whereas the bump provides a local mechanism to maximize the energy transfer rate.

- Has the full barotropic vorticity balance equation - obtained by integrating the momentum equations in the vertical and cross-differentiating them.

- Bottom pressure torque closely related to the bottom vortex stretching term (**?**)

- - "Make use of the relation between bottom pressure anomalies and bottom pressure torque $J(P_b, h)$ - the Jacobian of the bottom pressure and the detph of the topography h. For a terrain following model like ROMS Maybe some of the NEMO sigma coords? the bottom torque can be computed exactly by taking the curl of the vertically integrated horizontal pressure gradient. From the torque we can find ta pressure anomaly along a contour line of fixed topography depth using $p_b = -\int \frac{J(P_b,h)}{\partial h/\partial n} ds$ (n,s) are the right handed horizontal coordinates with s as teh distance along a contour. $\partial h/\partial n$ is the local slope.

- - "The bottom pressure torque $J(P_b, h)$ arises from variation of bottom pressure along isobaths. It derives from the twisting of the force that the bottom topography exerts on the ocean.

- - Use Fig 13 - showing mean bottom pressure torque - "The signal strongly reflects the bottom pressure torque"... "The large negative signal where teh tstream encounters teh tip of the bup corresponds to the incoming flow going uphill. There are two large positive signals downstream on both sides of the stream where the flow is locally going downhill, followed by smaller negative signals where the flow is going uphill again."

- - "The bottom pressure torque represents the contribution of the topography to the barotropic vorticity evolution of the flow."... "The bottom pressure torque is the term locally enabling the return flow of the wind-driven transport in western boundary currents and providing most of the overall positive input of vorticity balancing the negative input by anticyclonic wind culr on the scale of the gyre."

- - Locally a very large cancellation between the bottom pressure torque and the nonlinear advection terms - "This results from the balance between pressure forces and inertia around small-scale topographic features."

- - dominant terms are the bottom pressure torque, nonlinear advection, bottom drag curl and planetarty vorticity advection. The other terms (rate of change of vorticity, horizontal diffusion and wind stress curl) are all at least an order of magnitude smaller compared to the others.

Full barotropic vorticity balance equation Obtained by integrating th emomentum equations in the vertical and cross-differentiating them:

$$\frac{\partial \Omega}{\partial t} = -\nabla.(f\bar{\mathbf{u}}) + \frac{\mathbf{J(P_b, h)}}{\rho_0} + \mathbf{k}.\nabla \times \frac{\tau^{wind}}{\rho_0} - \mathbf{k}.\nabla \times \frac{\tau^{bot}}{\rho_0} + \mathcal{D}_\Sigma - A_\Sigma \tag{18}$$

These terms are: rate, planetary vorticity advection, bottom pressure torque, wind curl, bottom drag curl, horizontal diffusion, Non-linear advection.

5 Mertz1992

(Mertz and Wright, 1992)

- Well established that baroclinicity and sloping bottom topography can give rise to a driving force for the depth-averaged flow.
- Clearest expression of JEBAR effect obtained whena vorticity equation is formed from the depth-averaged momentum equations. The JEBAR effect is then represented by a single term 0 the Jacobian of a potential energy anomaly and depth.
- Clearest physical discussion of JEBAR available is given by Holland (1973) based on teh curl of the depth-integrated momentum equations. In this case JEBAR effect enters implicitly through its influence on the bottom pressuer and associated bottom torque.
- Start with linearized horizontal momentum equations and the continuity equation. Separate velocity into components driven by the pressuer gradient and frictional stress. First approach: depth average the inviscid versions of the momentum equations, then cross differentiate to eliminate the pressure terms. This yields an equation for the rate of change of the vortiicty of the depth-averaged flow.
- Using above, yields:

$$\bar{\xi} + H\bar{\mathbf{u_p}} \cdot \nabla \frac{f}{H} + \frac{f}{H} \nabla \cdot (H\bar{\mathbf{u_p}}) = J(\chi, \frac{1}{H}) \tag{19}$$

  where $\chi = \frac{g}{\rho_0} \int_(-H)^0 z\rho dz$ and $J(A,B) \equiv A_x B_y - B_y A_x$ yielding

$$JEBAR = J(\chi, \frac{1}{H}) \tag{20}$$

- They then use maths trickery to eliminate the divergence term from 19 yielding:

$$\xi + \bar{\mathbf{u_p}} \cdot \nabla f - \frac{f}{H} \bar{\mathbf{u_p}} \cdot \nabla H = \frac{f}{H} curl_z [\frac{\mathbf{S_s} - \mathbf{S_b}}{\rho_0 f} + J(\chi, \frac{1}{H}) \tag{21}$$

  Relating to the change of the vorticity of the depth-averaged flow to the transport across contours of constant planetary vorticity (second term on LHS), topographic vortex stretching (3rd term on LHS), surface forcing and bottom damping (1st term on RHS) and JEBAR (2nd term on RHS). This is equivalent to that of a homogenous fluid, except for the JEBAR term - which is a manifestation of the baroclinicity of the fluid.

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- So far interpretation of JEBAR has been as a correction to the topographic vortex-stretching term in the depth-averaged vorticity equation.

- Can also interpret JEBAR by relating it to the bottom torque - the curl of the horizontal force exerted by the bottom on the fluid.

Depth-integral version - JEBAR as torque Define a streamfunction Ψ such that,

$$\Psi_x = \int_(-H)^0 vdz, quad - \Psi_y = \int_(-H)^0 udz \tag{22}$$

and depth integrate the linearized momentum equations governing the horizontal velocities:

$$u_t - fv = -\frac{1}{\rho_0} p_x + \frac{1}{\rho_0}\frac{\partial}{\partial z}\tau^((x)) \tag{23}$$

$$u_t + fu = -\frac{1}{\rho_0} p_y + \frac{1}{\rho_0}\frac{\partial}{\partial z}\tau^((y)) \tag{24}$$

So vertically integrate 23 and 24 and cross-differentiate to obtain:

$$\nabla \cdot \nabla \Psi_t + J(\Psi, f) = \frac{1}{\rho_0} J(p_b, H) + curl_z[\frac{\tau_s - \tau_b}{\rho_0}] \tag{25}$$

This is exactly the same form as for a homogeneous or stratified fuid. The first term on RHS is the topographic torque term. Rewriting it as

$$\frac{1}{\rho_0} curl_z(p_b \nabla H) \tag{26}$$

emphasises that it's the curl of the horizontal component of the force normal to the bottom exerted by the bottom on the fluid.
To relate bottom torque to JEBAR, use (11) to show:

$$\frac{1}{\rho_0} curl_z(p_b \nabla H) = \frac{1}{\rho_0} curl_z(\bar{p} \nabla H) - curl_z[\frac{\chi \nabla H}{H}] \tag{27}$$

6 Yeager2015

(Yeager, 2015)

- "They pointed out that JEBAR arises because topography causes the PV contours at difference depths (densities) to diverge, and so circula- tion that is essentially baroclinic (with PV-conserving flow in each layer) can acquire a barotropic component (which does not follow barotropic PV contours)"
- "Zhang and Vallis (2007) have shown that the BPT associated with deep western boundary current (DWBC) flow offshore of the Grand Banks is a key factor in setting the strengthof the northern recirculation gyre (NRG)the cyclonic, barotropic flow that has been observed between the northern flank of the GSand the Grand-Banks (Hogg et al. 1986). They showed that BPT-related changes in the NRG can influence the GS path after separation from Cape Hatteras."
- "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"
- "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"
- "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 "

7 NaveiraGarabato2013

(Naveira Garabato *et al.*, 2013)

- Dynamical ocean balance - between acceleration of the ocean by wind sterss and a deceleration by pressure forces on bottom topography. - cites Geoff's book.
- They illustrate the above using the depth integrated momentum equation (w/ steadiness assumed).

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