Two Gyres revisited: Branches, bifurcations, and retroflections over the Tail of the Grand Banks of Newfoundland

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Historical Context

Thirty-two years ago Worthington published his monograph "On the North Atlantic Circulation." A central feature of his synthesis of circulation estimates and interpretations was his "Two-Gyre hypothesis," descended from a concept he first put out in 1962.

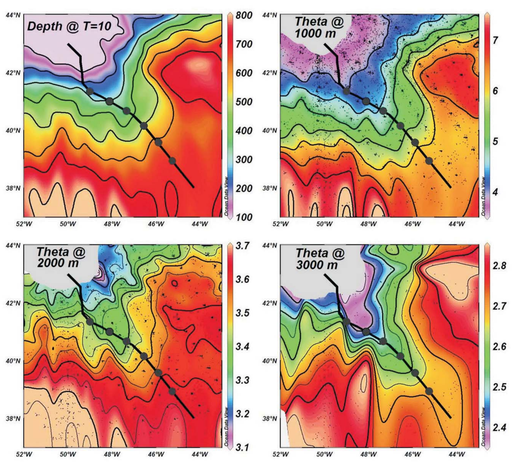
His idea was that the large transport he estimated for the eastward flow of the Gulf Stream south of Nova Scotia wholly recirculated west of the Tail of the Grand Banks, and that the large northward recirculation that he estimated for the North Atlantic Current east of Newfoundland was a separate closed "Northern Gyre." No Gulf Stream branch to the North Atlantic Current was included, which became the focus of controversy.

There has been much work since then. In 1993 Bill Schmitz and Mike McCartney undertook a synthesis of the whole North Atlantic, to update Worthington's monograph in light of new observations and interpretations, notably measurements confirming Worthington's 150 Sv Gulf Stream estimate. The Tail of the Grand Banks remained an area of great uncertainty: they recognized that there at least needed to be a Gulf Stream Branch into the North Atlantic Current to maintain the continuity of warm water meridional transport through the Meridional Overturning Circulation (MOC), a minimal transport of order 13 Sv. But they found no other constraint for the total branch strength.

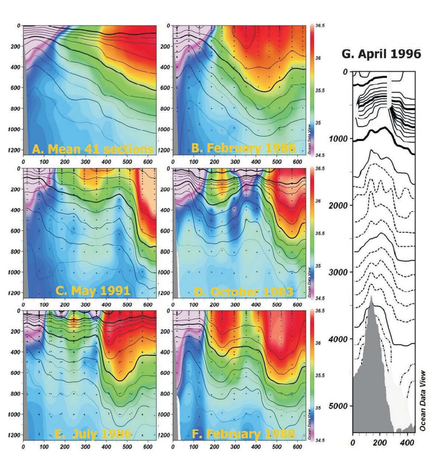
We have explored the implications of new measurements subsequent to the Schmitz and McCartney synthesis. Two things have motivated us to again reexamine the regional circulation around the Tail of the Grand Banks:

I. A definitive measurement (A. Clarke, C. Meinen and colleagues) of North Atlantic Current (NAC) transport as 140 Sv, even stronger than Worthington's original estimate of 74-97 Sv, due to appreciable northward bottom velocity at its base. Can we estimate the fraction of the Gulf Stream's 150 Sv eastward transport towards the Tail that branches and turns across the Tail, initiating the northward flow of the North Atlantic Current? How much of the Gulf Stream (GS) instead retroflects into the recirculations to the north and south of the Stream?

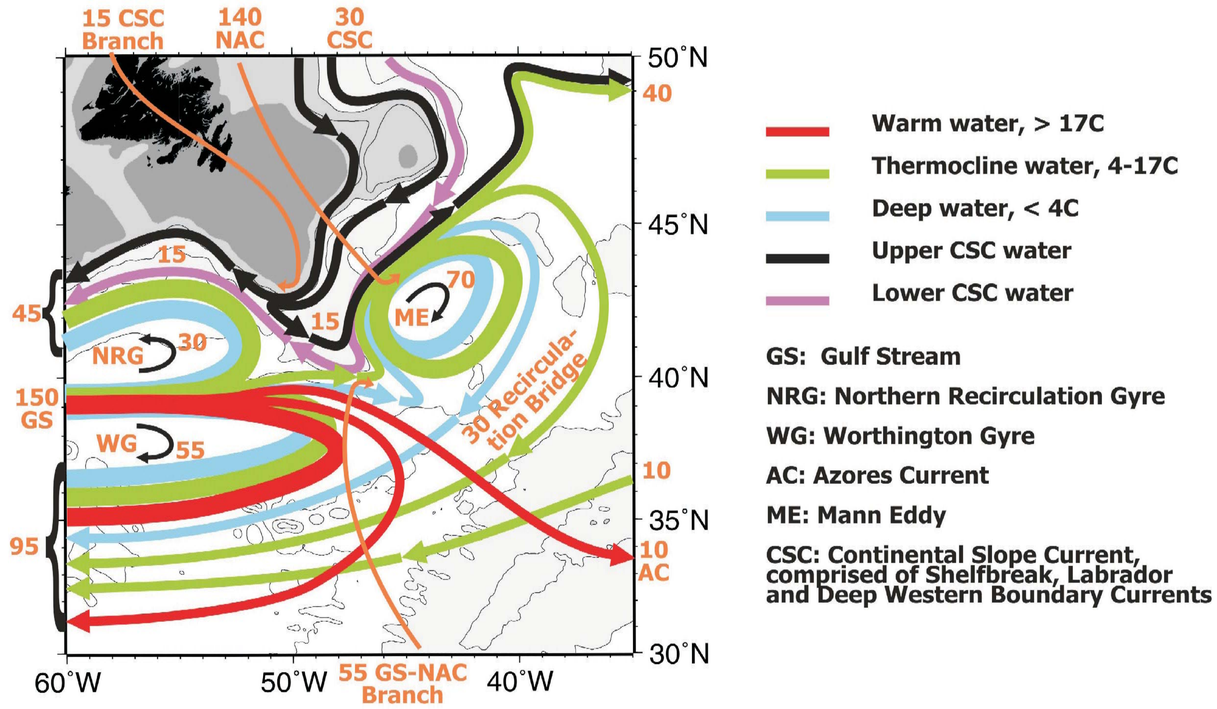
II. Equatorward flow along the western boundary is dominant from north of Newfoundland south to Cape Hatteras, spanning bathymetric depths from the shelfbreak across the upper continental slope, and down through the dense levels of the Deep Western Boundary Current (DWBC). How does that system, the "Continental Slope Current" (CSC) negotiate the "close encounter" with Gulf Stream Branch crossing the Tail of the Grand Banks? There is growing evidence that not all the waters flowing southward east of the Grand Banks turn west across the Tail, but instead retroflect back northward with the NAC. Can we estimate that retroflection of the Continental Slope Current? Recent DWBC measurements (a. Clarke, F. Schott, J. Fisher and colleagues) near 42ºN well-constrain the DWBC transport approaching the Tail from the north.



The maps show the Trough as it appears in climatological averages of hydrographic data. The Tail's Spine axis is overlaid. Shown are the depth of the 10ºC isotherm, which is a proxy for thermocline shear, and theta at 1000 m, 2000 m and 3000 m. Data coverage ≤ 2000 m is dominated by the massive USSR surveys between 1982 and 1991. These surveys represent 30 well-resolved synoptic surveys in the domain during that period. Individual sections have larger numbers of repeats.



Schematic of the estimated circulation south and east of the Grand Banks of Newfoundland



Constraining the Regional Circulation

Integrating the measurement of 140 Sv for the North Atlantic Current strength into the synthesis of Grand Banks regional circulation reveals significant uncertainties for the strengths of Branches, Bifurcations and Retroflections around the Tail of the Grand Banks. These can be reduced to two unresolved questions:

To what degree does the eastward flowing Gulf Stream south of Nova Scotia and Newfoundland branch northeast across the Tail of the Grand Banks to feed the northward flowing North Atlantic Current east of the Grand Banks?

To what degree do the southward flowing currents over the shelfbreak and continental slope east of Labrador and Newfoundland branch southwest across the Tail of the Grand Banks to feed the westward flowing Continental Slope Current south of Nova Scotia and Newfoundland versus retroflecting back northwards into the North Atlantic Current?

Our synthesis enables setting ranges for the two dominant circulation branches at the Tail: 25 – 85 Sv for the GS-NAC Branch and 5 – 25 Sv for the CSC branch.

For the Gulf Stream branch across the Tail to the North Atlantic Current, the minimum, 25 Sv is that required to support the warm water transformed in the MOC, and thermocline waters that flow towards Ireland to the eastern basin and recirculate southwards in the eastern basin. The upper limit of the Branch, 85 Sv, is principally set by measured and estimated strengths of the Worthington Gyre and Northern recirculation gyres, respectively south and north of the Gulf Stream, which are each fed by reflections from the Stream. Our estimate is that between 17% and 57% of the 150 Sv Gulf Stream branches across the Tail to the North Atlantic Current, and thus that only 18% to 61% of the North Atlantic Current Strength

For the branching of continental Slope Current water westward across the Tail, the minimum limit 5 Sv, reflects the presence of northern source water within the DWBC to the west of the Tail, while the upper limit, 25 Sv is set from combining the measurements of DWBC to the north of the Tail with upper limits of its error and of estimated upper continental shelf and shelfbreak current contributions to CSC transport.

For the illustration here, we have adopted in this schematic values in the middle of those ranges: a 55 Sv GS Branch northeastward across the Tail to the NAC, and a 15 Sv CSC Branch westward across the Tail. These result in a Worthington Gyre Strength of 55 Sv, and a Northern Recirculation Gyre of 30 Sv.

Depending on the strength of the GS-NAC Branch and CSC Retroflection, an offshore Recirculation Bridge may be required for overall mass balance. With the above constraints on the ranges for GS and CSC branches across the Tail, this Recirculation Bridge is constrained to a range from 0 to 70 Sv. For the illustrated example, 30 Sv of the 40 Sv Bridge represents linkage between the Mann Eddy in the Newfoundland Basin (Worthington's "Northern Gyre) and the Worthington Gyre south of the Gulf Stream, while 10 Sv represents recirculation from the eastern basin passing north of the Azores.

The Structural Stability of Worthington's "Trough"

The eastward-flowing Gulf Stream approaches the Tail of the Banks with the character of an inertial zonal free jet. However, at the Tail significant changes occur (refer to schematic in the top row of poster):

(1) portions of the Gulf Stream diverge, retroflecting northwestward and southwestward to feed recirculation gyres adjacent to the Stream,

(2) a branch of the Gulf Stream Stream swings northward across the Tail, feeding the North Atlantic Current, and

(3) a residual transport continues east feeding the Azores Current.

The meridional flow of the North Atlantic Current marks the momentary reestablishment of a western boundary current. The transition of the Gulf Stream Branch from a separated free jet back to a western boundary current configuration is a phenomenon unique to this basin of the world ocean.

Worthington noted that the extrusion of cold waters from the continental slope out along the Tail of the Grand Banks creates a low dynamic height area over the Tail, which he called "the Trough." Our interpretation is that the Trough configuration results from the interaction of the Gulf Stream Branch encountering the offshore deflection of the Continental Slope Current elements as they are deflected substantially south before turning west across the crest of the Tail. In that interaction of colliding currents the Gulf Stream Branch executes an essentially 90º turn from eastward to northward flow. Inshore of the Gulf Stream Branch the southward flow of the Continental Slope Current undercuts the Branch as it turns from southward flow, crosses the Tail, and flows westward into the Slope Water. The Trough thus is a manifestation of the geometry of the two opposing currents crossings of the Tail. The Though has a surprising stability of location, shape and strength, probably reflecting influence of the steep topography compared to the abyssal plain that the Gulf Stream flows over approaching the Tail. The four panels to the left to simple representations of the plan view of the Trough.

Stability of the Geostrophic Shear Distribution

Cross sections of potential density (contours) and salinity (color) running along the spine of the Tail.

(A) Climatological average showing the belt of northeastward shear overlying most of the spine, with limited southwestward shear on the upper continental slope and shelfbreak.

(B-F) Synoptic sections showing the most extreme northern and southern positions of the Trough front encountered in 41 realizations. The position of the Trough front is separated by just 200 km in the most extreme cases (compare B & C).

(G) A full water column section perpendicular to the spine, showing that the Trough involves monotonic geostrophic shear, oriented as poleward shear with respect to the bathymetry.

The shear distribution along the spine of the Tail must support the northeast-turning GS-NAC Branch and the northeast-retroflecting branch of the CSC, and, simultaneously, the southwest-turning CSC branch (including the DWBC and shallower elements including the Shelfbreak and Labrador Currents). Given the monotonicity of the shear over most of the Tail, the quantitative sorting out of the branches bifurcations and retroflections over the Tail transforms into the need to determine the level of no motion/ reference level velocity distributions along the Spine.

The Tail-induced Bottleneck hypothesis

The low pressure Trough over the Tail of the Grand Banks represents a Tail-induced bottleneck to the currents approaching the Tail from the west and north. The Trough must simultaneously support the northeast turning branch of the Gulf Stream and the southwest turning branch of the Continental Slope Current. This limits the sustainable strengths of the across-Tail branches of the approaching currents.

Our plan of attack on this hypothesis involves working on existing ocean observations to refine circulation estimates that underlie the quantitative schematic, and, in parallel, to examine model output from high resolution HYCOM simulations. In the remainder of this poster we describe some aspects of the regional measurements that our new analysis work have revealed, and describe a first look at HYCOM model output for this region.

Key Transport estimates and measurements constraining the regional circulation.

West of the Tail of the Grand Banks, the Gulf Stream transports 150 Sv towards the Tail.

Northeast of the Tail, the North Atlantic Current transports 140 Sv away from the Tail.

East of the Tail the Azores Current transports 10 Sv across the Mid-Atlantic Ridge.

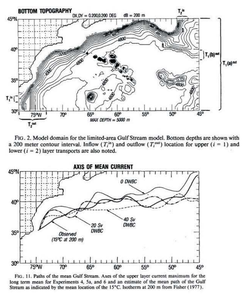
Between the North Atlantic Current and the Grand Banks, the Continental Slope Current transports 30 Sv southward.

Between the Gulf Stream and the Nova Scotia continental shelf, the Continental Slope Current transports 45 Sv westward.

Each of the above water column transports can be subdivided into separate contributions to the deep, thermocline and warm layers, so the estimates require transport consistency within the three layers as well as the full water column.

The meridional overturning circulation strength is constrained to about 15 Sv (10-20Sv), requiring a net southward flow of deep water of that strength east of the Grand Banks.

Exploring the interaction of the Gulf Stream and its Branch with the Deep Western Boundary Current.



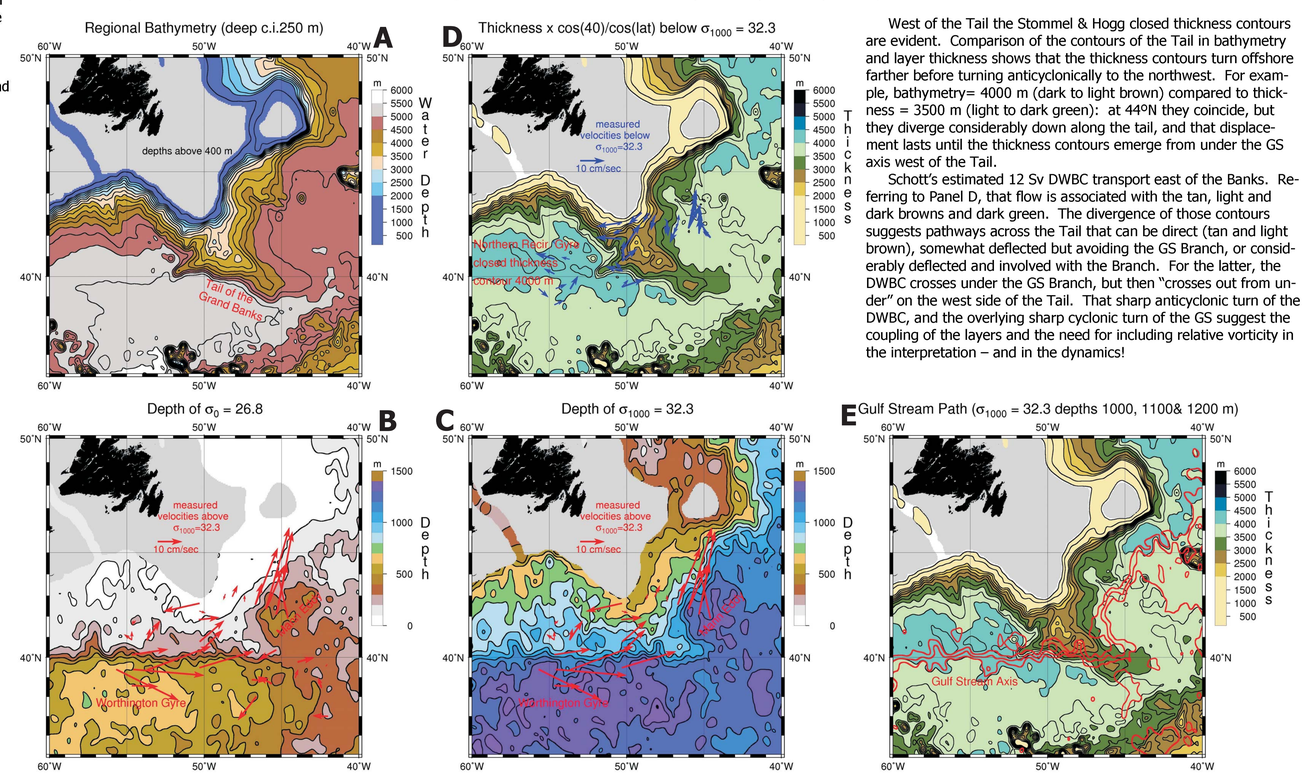
THOMPSON AND SCHMITZ, 1989

An early study my Thompson and Schmitz (1985), using a limited area numerical simulation, focused on how the absence or presence (and strength) of a DWBC entering the basin from the north altered the separation angle and pathway of the GS. But their pictures (left) hint the interaction of the entering DWBC with the Tail of the Grand Banks perhaps more directly effects the exit latitude of the GS. Zhang and Vallis (2007) have uses a series of simple and numerical models to conclude that a down-slope component of the DWBC induces downwelling that is strong enough to be an important factor in the GS separation at Hatteras and in forcing of the NRG, and particularly implicated the sharp curvature of isobaths at the Tail of the Grand Banks as inducing anticyclonic vorticity and though bottom friction a locally enhanced down-slope flow component. We present some attempts to discern the interaction of the DWBC and GS at the Tail, using an extension of a simple model by Hogg and Stommel.

Hogg and Stommel (1985) used a very simple dynamical framework to explore two phenomenon, the Northern Recirculation Gyre and the Deep Western Boundary Current's crossing under of the Gulf Stream at Cape Hatteras. For both regimes the same simple model was used, a two-layer system, where the interface (thermocline of the Gulf Stream) was a prescribed shape. This, of course, precludes considering the true interactive dynamics of the GS and DWBC. The deep layer thus has a distribution of thickness defined by the variations of the bathymetry and the interface depth, and the model considers the consequences of conserving potential vorticity for the lower layer. For the Hatteras region they included relative vorticity to diagnose how, for realistic shape of the interface, the DWBC upon encountering the north side of the GS, turns offshore as it descends under the GS, with thickness distortion due to the generation of relative vorticity, then settles into a new deeper bathymetric level after completing the cross-under of the GS. For the NRG region, they neglected relative vorticity and thus considered simply the f/thickness distribution that resulted for area south of Nova Scotia through the combined effects of bathymetry, latitudinal variation of f, and the southward descent of the interface across the GS. For reasonable smoothed representations of bathymetry and GS thermocline, they found most f/H contours pass through the region along the continental slope, but that between the foot of the continental slope and the southern side of the GS front, an area of closed f/thickness contours was found, closed to the west by the southward turn of the continental slope towards Hatteras, and in the east by the southward turn off the slope towards the Tail of the Grand Banks. They implicated this as the home of the NRG, a gyre recirculating around the closed contours driven perhaps by eddy forcing. We have adapted their very simple model as a tool to look at the Grand Banks region, with the first results show in the five panels below.

Panel A, the bathymetry, shows the dramatic Tail dividing the area into a deeper western basin, and the Newfoundland Basin, with maximum depths ~ 500-750 m shallower. Panels B and C show the depths of mid- and lower-thermocline GS isopycnals, both rising northwards across the GS by 500 m and. We have placed mean velocity vectors on the two charts from major arrays; these are instruments that line above the panel B density surface. The GS is a remarkably zonal front at about 40ºN. We adopt the deeper density surface topography as the interface to define a lower layer thickness distribution. This surface is close to a surface Schott et al (2004 $ 2006) have used as a top surface for estimating DWBC transport in the array east of the Banks.

Panel D combines the bathymetric and density surface depths to form a deep water thickness. To account for potential vorticity we normalize the resulting thickness by the ration of cosines for a standard latitude 40ºN and the local latitude. Thus with no relative vorticity effects, these adjusted thickness contours are the pattern of the f/H contours of the deep layer. We show current meter vectors from the same arrays, but those that measured beneath than our chosen density surface. In Panel E the same adjusted deep layer thickness is show, but with the GS path in the thermocline superimposed to show its sharp response, a 90º cyclonic turn, to encountering the DWBC at the Tail. This is the Trough described on the far left, and the figure shows that it lies above an ever sharper bend of the deep layer thickness contours at the southern area of the Tail. Under the supposition that the DWBC flows along those contours, this deep layer turn is a 180º anticyclonic switchback from southeast flow to north west flow.



West of the Tail the Stommel & Hogg closed thickness contours are evident. Comparison of the contours of the Tail in bathymetry and layer thickness shows that the thickness contours turn offshore farther before turning anticyclonically to the northwest. For example, bathymetry= 4000 m (dark to light brown) compared to thickness = 3500 m (light to dark green): at 44ºN they coincide, but they diverge considerably down along the tail, and that displacement lasts until the thickness contours emerge from under the GS axis west of the Tail.

Schott's estimated 12 Sv DWBC transport east of the Banks. Referring to Panel D, that flow is associated with the tan, light and dark browns and dark green. The divergence of those contours suggests pathways across the Tail that can be direct (tan and light brown), somewhat deflected but avoiding the GS Branch, or considerably deflected and involved with the Branch. For the latter, the DWBC crosses under the GS Branch, but then "crosses out from under" on the west side of the Tail. That sharp anticyclonic turn of the DWBC, and the overlying sharp cyclonic turn of the GS suggest the coupling of the layers and the need for including relative vorticity in the interpretation – and in the dynamics!