Earth, Moon, and Planets (2005) 94: 57–71
DOI 10.1007/s11038-004-7606-9 

# FUTURE GRAVITY MISSIONS AND QUASI-STEADY OCEAN CIRCULATION

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(Received 8 October 2004; Accepted 14 November 2004)

**Abstract.** The quasi-permanent sea surface slope, i.e. the signature of oceanic currents that does not vanish when dynamic topography observations are averaged over a long period of time, will be resolved up to spatial scales of about 100 km by the GOCE space gravity mission. However, estimates of the quasi-permanent ocean dynamic topography, derived qualitatively either from models or from observations, indicate that some non-negligible residual signal remains below 100 km in areas of strong surface currents like the core of the Gulf Stream. One therefore expects that future missions can improve our knowledge of the ocean circulation in these areas. However, the potential improvements are small compared to the improvements expected from GOCE itself.

## 1. Introduction

Although the ocean is known to be a highly variable medium, paleoceanographic and historical records show that oceanic currents have a strong quasi-permanent signature at the surface of the ocean. Reconstructions of sea surface temperature from assemblage of planktonic foraminifera indicate that a temperature front already crossed the North Atlantic 20000 years ago, thereby suggesting the presence of a glacial equivalent of the Gulf Stream (Keffer et al., 1988; Pflaumann et al., 2003). A chart of the Gulf Stream made by Franklin more than 200 years ago puts the current at the same location as the one indicated by modem instruments (http://www.oceansonline.com/ben_franklin.htm). Of course, the instrument record averaged over a significant amount of time does not correspond to the actual current itself, but rather to the envelope within which the current occurs because of recurring latitudinal shifts and meanders over distances of several hundreds of kilometres. The important point, however, is that the signature of the currents does not vanish when the observations are averaged over a long period of time, potentially as much as several tens of thousand years, whence the concept of quasi-steady ocean surface topography. This signature shows up in altimetric measurements, which span the last 20 years only, as a departure from the geoid.

One needs to estimate the quasi-permanent ocean surface topography in order to compute the absolute velocity of surface currents from altimetric data. Until now, only low precision climatological estimates derived from in situ hydrographic measurements are available down to spatial scales of 100 km (LeGrand et al., 2003). In the near future, the GOCE gravity mission will provide a precise estimate of the marine geoid down to these scales (ESA, 1999). The question arises, however, as to whether GOCE will be able to resolve the finest spatial scales associated with the quasi-permanent ocean circulation. The issue of whether future space gravity missions will still be needed after GOCE is thus investigated here.

Section 2 begins with a quick summary of theoretical arguments that constrain the spatial scales of the ocean circulation in terms of the Rossby radius of deformation. Section 3 compares several general circulation model estimates of the spatial scales associated with the mean circulation. In Section 4, qualitative observational estimates are shown to support the model results. In Section 5, miscellaneous ocean processes that can produce intense quasi-permanent dynamic topography gradients over spatial scales not resolved by GOCE are reviewed. A special emphasis is put on regions bordering continental boundaries and on the Mediterranean Sea because of the relatively small-scale of the dynamical processes that occur there. Finally, the question of the complementary data/models that would be required to make the best use of future high resolution gravity observations is examined.

## 2. Spatial Scales of Oceanic Currents: Theoretical Considerations

A classical problem in geophysical fluid dynamics, first studied by Rossby (1938), is the adjustment of a surface from an initial state in which all the energy is in the form of potential energy. In this problem, an initial step

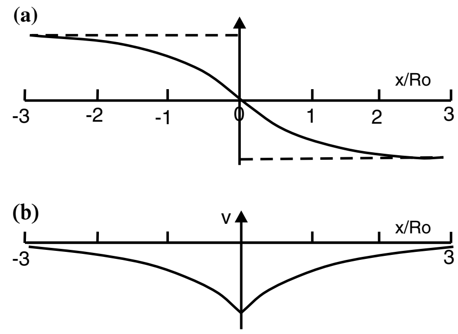


*Figure 1*. (a) initial step in sea surface topography (dashed line) and final topography after adjustment (full line). The horizontal scale is expressed in Rossby radii. (b) final geostrophic velocities (perpendicular to the plane).

function in sea-surface height (Figure 1a) is let to adjust under the forces of gravity and Earth rotation. The final state, obtained after the radiation of surface gravity waves, is not a state of rest but a geostrophic one (Figure 1b) in which potential energy has been converted into kinetic energy. Because of the coriolis force, the geostrophic flow is not in the direction of the pressure gradient, but at right angles, i.e. along contours of surface elevation that are parallel to the line of the initial step function. An interesting outcome of the adjustment is that the resulting geostrophic current, which has become steady after only a short time of the order of days, has a characteristic cross-stream spatial scale that is given by the Rossby deformation radius. This radius is $R_0 = (gh)^{1/2}/f$ where $g$ is the gravitational acceleration, $h$ is the water-depth, and $f$ the coriolis parameter. This radius is very large, several 1000 km, and thus is not relevant to the determination of the small spatial scales of geostrophic flows.

However, the same theory applies to the adjustment of an initial perturbation in the density field in a two-layer system (Figure 2). In this case, the initial potential energy is in the form of a step function in the position of the interface between the two layers of the fluid, i.e. in the form of a density anomaly on the left-hand side of the step. This initial step will adjust in the same way as the surface step, through the radiation of internal gravity waves. After a few days, the resulting steady state current will be in geostrophic balance with a cross-stream scale also set by a Rossby radius, not the barotropic radius introduced above, but the baroclinic Rossby radius $R_1 = (g'h)^{1/2}/f$ where $g' = g\delta\rho/\rho$ is the reduced gravity, $\delta\rho$ being the density difference between the two layers ($h$ is the thickness of the upper layer in the present case). The reduced gravity appears in the baroclinic radius because gravity no longer acts on the full density of sea water, but on the density difference between the upper layer of fluid and the lower one. Because, over most of the ocean, relatively warm surface waters overlie colder and thus denser deep waters, this two-layer baroclinic structure is characteristic of many oceanic processes. For $h = 1000$ m and $\delta\rho/\rho = 10^{-3}$ one finds a baroclinic radius of deformation on the order of 10 km. A more careful estimation carried out by Chelton et al. (1998) is presented in Figure 3. The most

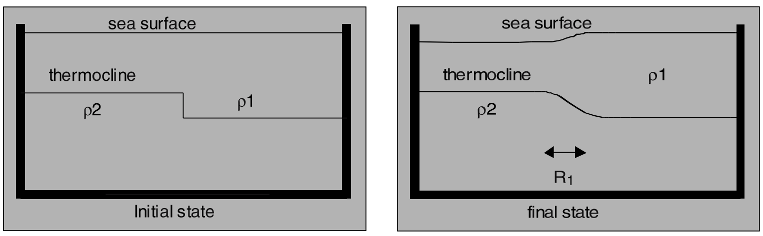


*Figure 2*. Initial step in the interface between two layers of fluid (the thermocline for instance) and final interface after adjustment.

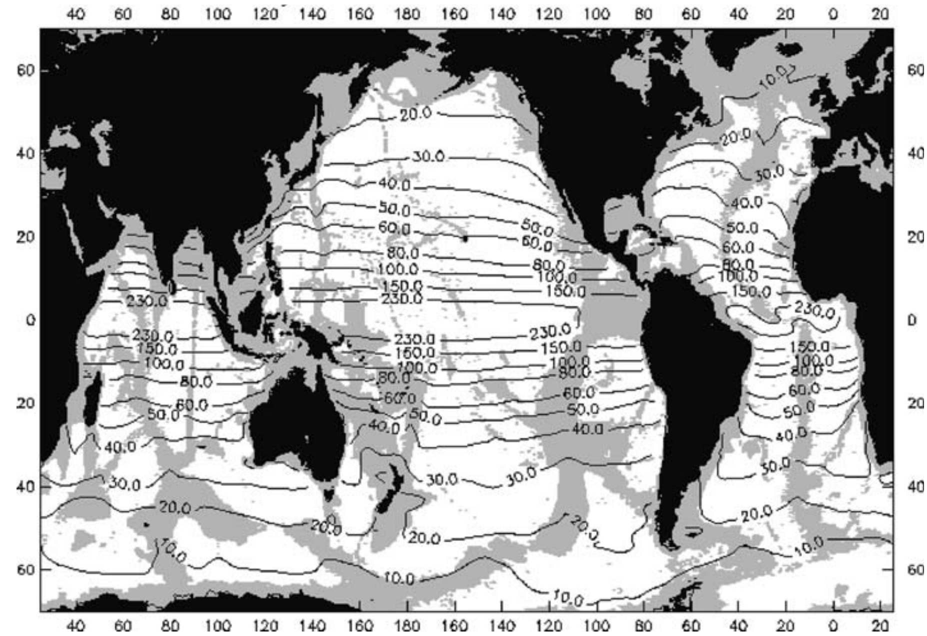


*Figure 3*. First baroclinic Rossby radius (km) over the world ocean (Chelton et al., 1998).

salient feature in this figure is the decrease of the radius going towards the pole caused by the increase of the Coriolis parameter. (Model results shown below are qualitatively consistent with this idea.) Thus, from theoretical arguments, one expects geostrophic currents to adjust to spatial scales beyond the reach of the 100 km resolution of the GOCE mission. Note that the adjustment of the interface between two layers of fluid has a signature at the surface of the ocean that can be detected from altimetric observations (the signal at the surface is much smaller than the signal at the interface between the two layers, unlike what is suggested in the schematic representation of Figure 2). Actually much of the ocean's variability seen by altimeters is associated with the first baroclinic mode (Wunsch, 1997).

In principle, geostrophic currents can occur at spatial scales even smaller than the first baroclinic Rossby radius. All that is required is that the magnitude of the nonlinear acceleration in the momentum balance is much smaller than the magnitude of the Coriolis acceleration caused by the rotation of the Earth. The first acceleration scales like $U^2/L$, $U$ being the current speed and $L$ its spatial scale, the second scales like $fU$. Thus, geostrophy remains a valid approximation if $U/(fL) \ll 1$. The left-hand side of the inequality defines the Rossby number. Therefore, geostrophy applies when the Rossby number is small. With current velocities on the order of 10 cm/s$^{-1}$, the geostrophic assumption is valid at mid latitudes (f$\sim 10^{-4}$ s$^{-1}$) as long as spatial scales of the currents are much larger than 1 km.

Geostrophic currents at these small spatial scales could for instance result from higher order baroclinic adjustments (adjustments of multiple layers of fluid). However, the associated surface signal in the open ocean is generally smaller than the signal associated with the first baroclinic mode and will probably be more difficult to observe.

## 3. Model Estimates of the Spatial Scales of Quasi-Steady Oceanic Currents

The characteristic spatial scales of various oceanic currents have been produced by Woodworth et al. (1998), leading to subsequent model estimates of the small spatial scales that will not be resolved by GOCE. The approach is synthesized in Le Provost and Brémond (2003). They use a 3-year average of the dynamic topography of the PAM 1/15° model to show that the amplitude of the associated small-scale dynamic topography signal can be as large as 5–10 cm in frontal zones like the Gulf Stream, the North Atlantic Current, and the East

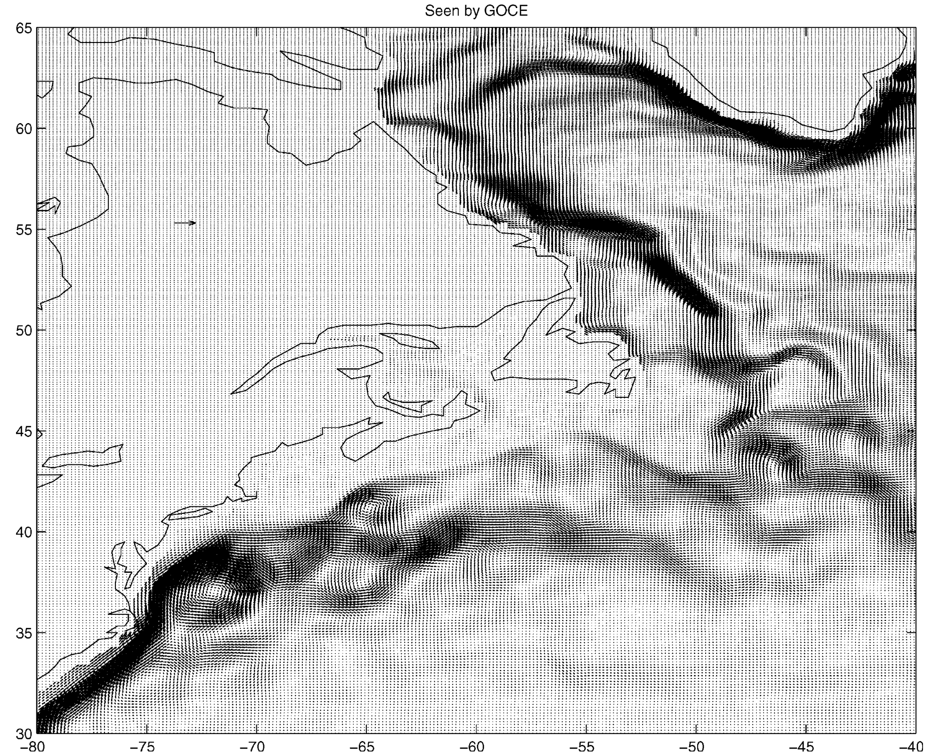


*Figure 4*. Velocity signal resolved by GOCE in a 5-year mean surface velocity field produced by the 1/6° CLIPPER model. (A filter that takes the median value of the six neighbouring points has been applied to the model output to extract the spatial scales of ~1° that will be resolved by GOCE.) Arrow in upper left corner indicates 1 m/s.

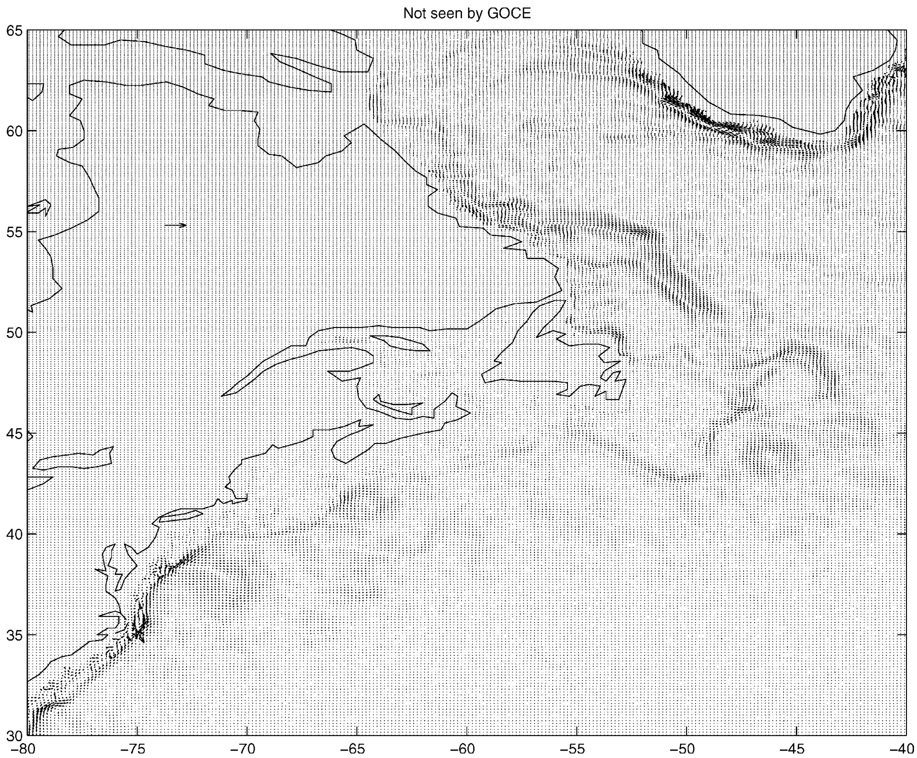


*Figure 5.* Velocity signal not resolved by GOCE. (The filtered velocity field of Figure 6 has been subtracted from the total 1/6° CLIPPER velocity field.)

Greenland Current (see their Figure 6). The signal that will not be resolved by GOCE is thus non-negligible and should be measurable from space. Le Provost and Bremond have compared the PAM estimate with other estimates from the MICOM and the POP high resolution models (see their Figure 3). MICOM exhibits the smallest spatial scales, on the order of 75 km. The small-scales expected from the baroclinic Rossby adjustment problem are thus not reached in the averaged model estimate. This is partly due to the fact that small-scale currents disappear in the averaged field, i.e. in the envelope within which the actual currents occur. It could also be due to the numerical diffusion present in the general circulation models, even in the very high resolution ones, which tends to smear out small-scale features. That the three different model calculations analyzed by Le Provost and Brémond (2003) give somewhat different estimates of the smallest spatial scales shows that the model results must be interpreted with caution.

In terms of current velocities, similar conclusions are reached. As an illustration, the velocity signal resolved by GOCE in another general circulation model, the 1/6° CLIPPER model (Treguier et al., 1999), is shown in

Figure 4 and the signal not resolved by GOCE is shown in Figure 5. From these figures, one sees that a gravity mission with a resolution higher than that of GOCE would allow better estimates of the small spatial scales of the Gulf Stream before it detaches from the coast, as well as better estimates of the Labrador Current. As mentioned above, the relatively large residual signal found in the latter region is consistent with the reduced Rossby radius at high latitudes. Elsewhere, i.e. in the interior of the basin, a high resolution mission would not add much to our knowledge.

Thus, numerical simulations indicate that future gravity missions will add to our knowledge of oceanic currents but the improvements, although non-negligible will be much smaller than those achieved by GOCE (LeGrand, 2001; Schroter et al., 2002).

## 4. Qualitative Observational Estimates of the Spatial Scales of Quasi-Steady Oceanic Currents

Because model estimates are not fully reliable, it is useful to check the model results using real data. Obviously, only qualitative checks can be made in the absence of a high resolution geoid. Two approaches are presented here that yield similar results.

A first approach is to look at sea level anomalies observed from altimetry and average them over some period of time. The idea is that the quasi-steady dynamic topography, which is the quantity of interest, has spatial scales qualitatively similar to those of averaged sea level anomalies. Indeed, dynamic topography is the sum of three terms

$$< \eta > = < \mathrm{sla} > + \mathrm{mssh} + g,$$

where $< \eta >$ is the dynamic topography averaged over some period of time, mssh is the mean sea surface height to which sea level anomalies (sla) are referenced, and $g$ is the geoid. Computing mssh and sla using the first 5 years of $T/P$ data and then, for example, averaging $\eta$ and sla over the third year of $T/P$ observations, one obtains $< \eta >$ as a function of $<\mathrm{sla}>$ for this year. $<\mathrm{sla}>$ can be easily computed for a particular pass of $T/P$, Pass 96 for instance between Greenland and Galicia (Figure 6). The one-year $<\mathrm{sla}>$ does not contain contributions from the geoid since the sla averaged over 5 years is zero by definition and any unknown geoid contribution goes into the mssh term. Thus, it seems reasonable to assume that the spatial scales contained in $<\mathrm{sla}>$ are qualitatively representative of the spatial scales contained in $< \eta >$. $< \eta >$ in turn is probably representative of the quasi-steady state signal since most dynamical processes acting on a one year average estimate also act on the quasi-steady circulation, and the amplitude of longer-term topography variations are relatively small. Small-scale

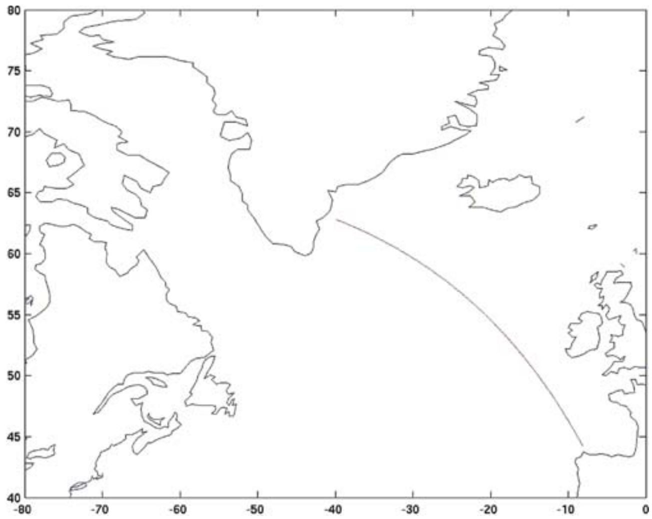


*Figure 6*. Location of *T*/*P* Pass 96.

features are clearly present in the estimate of < sla > shown in Figure 7, for instance the 3 cm downward-slope occurring over the [1100–1150 km] segment of Pass 96. This few centimetre residual signal at a spatial scale of 50 km is consistent with the numerical model estimates, although the spatial scales found here are slightly smaller, and agree better with the Rossby radius argument.

A more complete calculation by Uchida and Imawaki (2003) combines altimetric observations of temporal variations of the sea surface height with surface drifter data to compute the absolute flow field. The resulting estimate of the mean flow field exhibits small spatial scales in the North Pacific (Figure 2a of Uchida and Imawaki, 2003) that are visually consistent with the present estimate. Unfortunately, no quantitative estimate of the signal left below 1° is provided in their paper.

A second approach is to use recent estimates of the mean wind stress curl from the QuickScat satellite radar scatterometer. Indeed, wind stress is the main driver of the ocean circulation, especially in surface layers. Moreover, it is itself affected by the underlying oceanic surface currents, so that wind stress curl patterns are attributable primarily to ocean velocities in the Gulf Stream area (Chelton et al., 2004). Figure 8 shows a map of the mean wind stress curl derived from QuickScat observations in the North Atlantic. Figure 9 shows the same map where only spatial scales smaller than 1° have been retained. This map confirms the results of the CLIPPER simulation, with some significant signal left in regions of most intense oceanic currents. The percentage amplitude of the remaining signal tends to be larger than what was found in the CLIPPER model, as much as 50% of the total signal in the

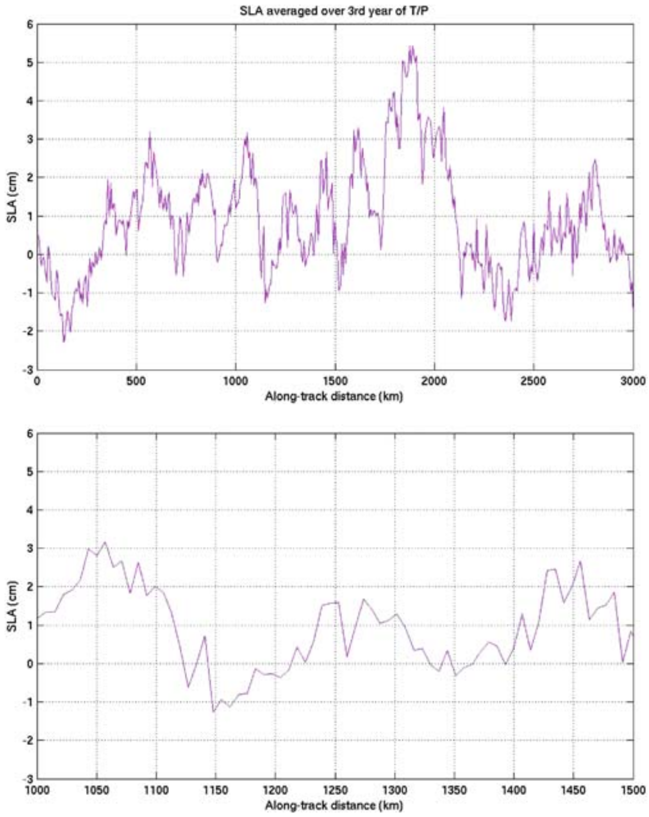


*Figure 7*. Upper panel: sea level anomaly between Greenland and Galicia averaged over the third year of *T/P* observations. Lower panel: zoom over the 1000 km–1500 km segment.

Gulf Stream before separation at Cape Hatteras. This result must be interpreted with caution, however, as the QuickScat data used here have been gridded prior to processing and only have a ½° resolution.

One therefore expects from qualitative observational estimates of the spatial scales of oceanic currents that future gravity missions could still improve estimates of the quasi-steady general circulation of the ocean after GOCE is flown. A resolution of the order of 50 km would be required with a precision better than the centimetric level. The impact on our knowledge of the quasi-steady state circulation would be significant, albeit limited.

## 5. Miscellaneous Particular Cases

Various processes may not be apparent in the global quasi-steady state ocean circulation, but still be of importance in local areas. A number of these processes are reviewed here, together with their implications in terms of future gravity missions.

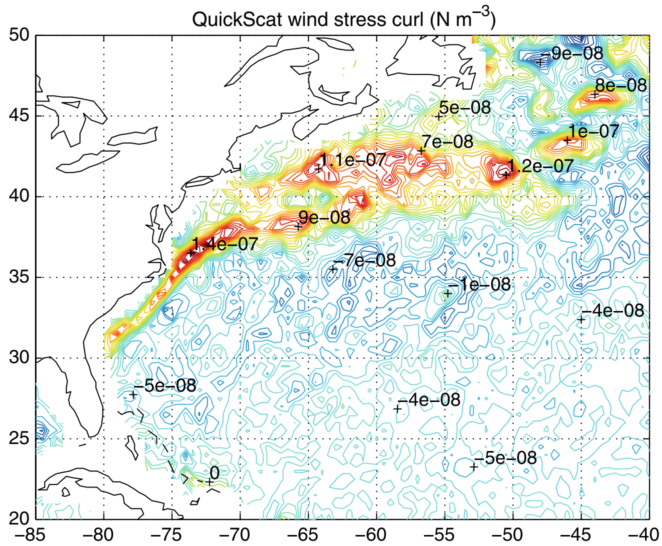


*Figure 8*. QuickScat observations of a 3 year-mean of the wind stress curl (Nm$^{-3}$). Data kindly provided by B. Chapron as a ½ ° gridded field.

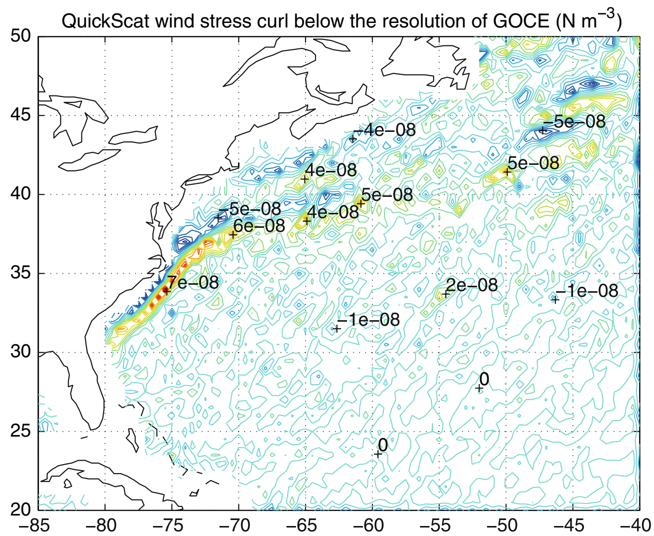


*Figure 9*. High-pass filtered (100 km) version of Figure 8. The filter is a simple two-dimensional median filter. The gridded observations are first averaged over neighbouring data points and are then subtracted from the original field. Qualitatively similar results are obtained using a two-dimensional Wiener filter.

### 5.1. Bathymetric control of the mean flow

A class of physical processes that can cause steep mean dynamic topography gradients is the one resulting from the interaction between the flow field and the bathymetry of the bottom of the ocean. A well-known theoretical example is a jet flowing above an isolated seamount. In this example, streamlines of the flow, i.e. the dynamic topography at the surface of the ocean, tend to get closer according to the spatial scales of the underlying bathymetry (for an illustration, see Gill, 1982, p. 315). Similarly, spatial scales of flows across narrow straits (Gibraltar Strait, Florida Strait, etc.) are very strongly constrained by the underlying bathymetry. Typically, these spatial scales are a few 10s of km and will not be resolved by the GOCE mission. One therefore expects that in these areas a future high-resolution quasi-steady state mission would lead to improved estimates of the ocean circulation. Although limited in their extent, these areas are important because of their impact on the general circulation of the ocean (the spreading of Mediterranean salt tongue for instance).

### 5.2. Near-shore and regional oceanography

An area of great societal importance that contains intense small-scale oceanic currents is the continental boundary of the oceans. Over continental shelves, and along continental slopes, intense currents occur over spatial scales of a few 10s of km. Many of these currents being approximately in geostrophic balance, particularly the downstream component of along-slope currents (Gill, 1982, p. 378), they can be observed from space altimetry. The question, however, is whether there is any quasi-permanent signal associated with this circulation. Indeed, large temporal variations occur near-shore (including tidal variations) that dominate the signal of persistent currents. Because coastal regions are difficult to monitor because of human activities (current meter moorings for instance, are difficult to maintain near-shore because of fishing activities), little is known about the mean circulation there. The little available observational evidence hints at some relatively stable currents along the shelf break, in the Bay of Biscay for instance (B. Le Cann, personal communication). Similarly, numerical simulations exhibit a mean dynamic topography signal associated with the extension of the North Atlantic Current along the north-western coast of the UK (Figure 7 in Haines et al., 2003). It is already possible to observe these currents from satellite altimetry by computing regional estimates of the geoid through the combination of existing geoid models with in situ gravity measurements (Haines et al., 2003). Unfortunately, there are few regions where the in situ gravity data base is sufficient to undertake this approach and a remote sensing approach is required for a global coverage.

The GOCE geoid is unlikely to resolve near-shore currents because the spatial scales of the currents tend to be set by the spatial scales of the continental shelf and the continental slope, i.e. often a few 10s of km. Future very high resolution gravity missions would therefore be useful to monitor coastal regions. Were the quasi-permanent currents found to be missing, this information would in itself be interesting considering how little is known on the subject.

Another area of great societal importance is the Mediterranean Sea, which is not only bordered by very densely populated countries, but is also characterized by small baroclinic Rossby radii that are on average 11 km (Grilli and Pinardi, 1998). The spatial resolution of gravity missions would therefore matter there more than in the open ocean.

Thus, improving the knowledge of the regional and near-shore quasi-permanent ocean circulation would require very high resolutions between 10 km and 50 km and high precisions (below the centimeter level) because the mean signals, although potentially important, may be relatively weak there.

### 5.3. Eddy-mean flow interactions

The study of eddy-mean flow interactions is important because of the role of eddies in redistributing momentum and heat in the ocean. In the atmosphere, where eddies have large spatial scales and are thus easier to monitor, it is known that they strongly interact with the mean flow. In the ocean, their role is less clear. Their spatial scale, which is of the order of the first baroclinic Rossby radius (Smith and Vallis, 2001), and the fact that they are ubiquitous suggest that their monitoring should be carried out from space. The problem, however, is that the mean flow being largely unobservable from altimetric data, it is not possible to evaluate precisely the mean position of fronts. Hughes and Ash (2001) show that, depending on whether the mean position of fronts in the Southern Ocean is more accurately reflected in satellite observations of sea surface temperature or in climatological in situ observations, eddies can be shown to either decelerate or accelerate the mean flow. GOCE, by providing precise and reliable observations of the mean position of fronts will improve our understanding of eddy-mean flow interactions. However, considering that eddies have spatial scales of the order of 100 km or smaller, and that topographic steering can produce very narrow jets, the resolution of GOCE may not be sufficient everywhere to accurately monitor these interactions. Future gravity missions that provide high resolution estimates of the geoid down to the Rossby radius in the Southern Ocean, i.e. a few 10s of km may thus be required, a precision at the centimeter level being probably sufficient.

## 6. Ancillary Data Sets

One last issue that needs to be examined is what ancillary data sets are required in order to estimate the steady circulation in combination with a high resolution quasi-steady state gravity mission, and what improvements in these data sets may be necessary.

The first complementary data set is altimetry. If one is to observe the small scales of the quasi-permanent circulation at the surface of the ocean, then altimetry must match the resolution of the gravity observations. The advent of wide-swath altimetry is very promising in this respect since this new generation of altimeters is expected to resolve spatial scales as small as 15 km while maintaining the precision level of the current generation of altimeters (Rodriguez and Pollard, 2001). Satellite altimeters of the class of Topex/Poseidon and Jason are satisfactory in terms of precision but lack the adequate resolution in between tracks, unless several such satellites are flown simultaneously on different tracks.

Where available, in situ local gravity measurements, can greatly help in achieving the highest possible resolution and thus complement space measurements, as shown in Haines et al. (2003).

Because altimetry and gravity constrain the quasi-steady circulation at the surface of the ocean only, they need to be complemented with in situ observations in order to estimate the three-dimensional quasi-permanent flow field. No miracle is to be expected there because of the difficulty of collecting in situ measurements. The ARGO network of profiling floats (http://www.ifremer.fr/coriolis/cdc/argo.htm) already provides three-dimensional observations of temperature and salinity, but mostly in the upper 2000 m. Even this automated network leaves out big gaps in remote areas like the Southern Ocean, along the northern coast of Brazil, and in many other important regions.

Finally, precise estimates of the wind stress over the ocean, similar to those provided by the QuickScat mission, are needed in order to estimate the non-geostrophic Ekman transports in the upper layer of the ocean. It seems that the available observations are already satisfactory (see Chelton et al., 2004). However, one has to ensure that this high quality space measurement capability is maintained in the future. A solution could come from the incorporation of satellite scatterometer observations in the activities of operational agencies like EUMETSAT in Europe or NOAA in the US.

## 7. Conclusion

Provided that the complementary data sets enumerated above are available, particularly high resolution altimetry and scatterometer observations, one expects that some room will still be left after the GOCE mission for improvements in estimates of the quasi-permanent ocean circulation. A future very high resolution gravity mission resolving spatial scales of about 50 km would be required. It seems reasonable to expect that improved estimates of these scales of the ocean circulation could locally lead to corresponding improvements in estimates of heat transport. However, obtaining observations of the three-dimensional temperature field on a 50 km grid would be very difficult in the global ocean.

The improvements provided by a future high spatial resolution mission would by no mean match those expected from the GOCE mission. However, processes like intense oceanic fronts, shelf-break currents, and flows in semi-enclosed seas could be determined more accurately. Most of these processes have small geographical extents, but they can have a strong impact on the global circulation and are of great societal importance.

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