Overview of Ocean Thermal Energy Conversation capabilities, using Mercator GLORYS2v1 Reanalysis

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1. Introduction

Oceanographic expertise can help to provide an overview, in order to know where Ocean Thermal Energy Conversion (OTEC) industry could be efficiently raised. OTEC industrial constraints are basically known: vertical temperature gradient, depth of the deep water collecting system, vicinity to distribution area (distance to the coast), type of bathymetry, hydrodynamical constraints (currents, vertical shear, sea state…).

Ocean reanalysis are good tool to describe the thermodynamics of the ocean in the past. A first attempt using numerical simulation (HYCOM+NCODA) has been provided in order define the potential useful of OTEC on a limited area, around the Hawaiian Islands [*Nihous*, 2010].

At Mercator Océan, the approach is to use ocean global reanalysis in order to map globally the potential OTEC areas. The horizontal resolution (1/4°) allows offering a good overview at large and medium scales for both thermodynamics and hydrodynamical constraints. Then dedicated approach, using higher resolution representation should be used for local studies.

A first attempt has been performed using the 2002-2009 Glorys1v1 global reanalysis, and focusing on the La Réunion Island [*Chayriguet*, 2010].

The present study is based on the 1992-2009 Glorys2v1 (G2V1) global reanalysis.Using this longer time period, the main goal is to establish areas on the global ocean that correspond to OTEC criteria.

Section 2 describes the Glorys2v1 reanalysis. Section 3 details the main results.

2. Description of Glorys2v1

Write overview of Glorys2v1, accuracy and benefit for OTEC studies

3. Thermal content and dynamical analysis

3.1. Relevant criteria for OTEC mapping

The following industrial engineering constraints, are taken into account for determining potential areas for OTEC:

- Minimum vertical temperature gradient of 20°C
- Maximum depth for collecting deep cold waters of 1000 m
- Maximum general circulation currents on the water column of (2 m/s?)?
- Maximum shear on the water column of ?

The two last constraints are more indicative: a dedicated representation of local hydrodynamics, including tides should be used to determine, then and exclude non appropriate areas.

3.2. Thermal content description from the climatological cycle

From the 1992 to 2009 G2V1 daily outputs, monthly averages have been computed. Then a climatological series has been built up using these monthly averages, as well as an annual climatological value.

3.2.1. The 1000-m depth limit constraint, using the 20°C vertical gradient criteria

Considering the fact that pipes collecting cold water in the deep ocean are limited to 1000-m depth, first question is what is the temperature gradient from the surface to 1000-m depth?

Figure 3-1 shows that from 0 to 1000-m depth, temperature differences larger than 16°C are limited to tropical areas, where warm surface water are separated by a sharp thermocline to cold deep waters. A 20°C vertical temperature gradient is the other constraint for deploying OTEC industrial plants. The corresponding 20°C gradient isoline depicts areas of interest that follow the surface warm waters distribution in the tropics. They correspond to large areas in the western side of ocean basin, due to warm pool, and smaller areas in the eastern side, due to up-welling cold waters influence.

There is a seasonal variability changing surface warm waters distribution. To address that, a first approach is to look at the G2V1 climatological years. Figure 3-2 show also the surface to 1000-m depth temperature gradient from the G2V1 annual climatology, but the 20°C vertical temperature gradient for each of the 12 climatological months has been overlaid. Along the year, the 20°C limit is going to shift by several hundreds and thousands of kilometres in latitude.

The limits of the area of interest can be drawn looking at the statistics of these temperature difference mapped globally. Figure 3-3 provides the maximum area where the 20°C vertical difference (here from 5 to 1000-m-depth) is obtained: the red isoline, corresponding to location on the ocean where, at least once during the climatological cycle, this gradient is observed. The blue line corresponds to location where this gradient is always obtained over the 12 climatological months.

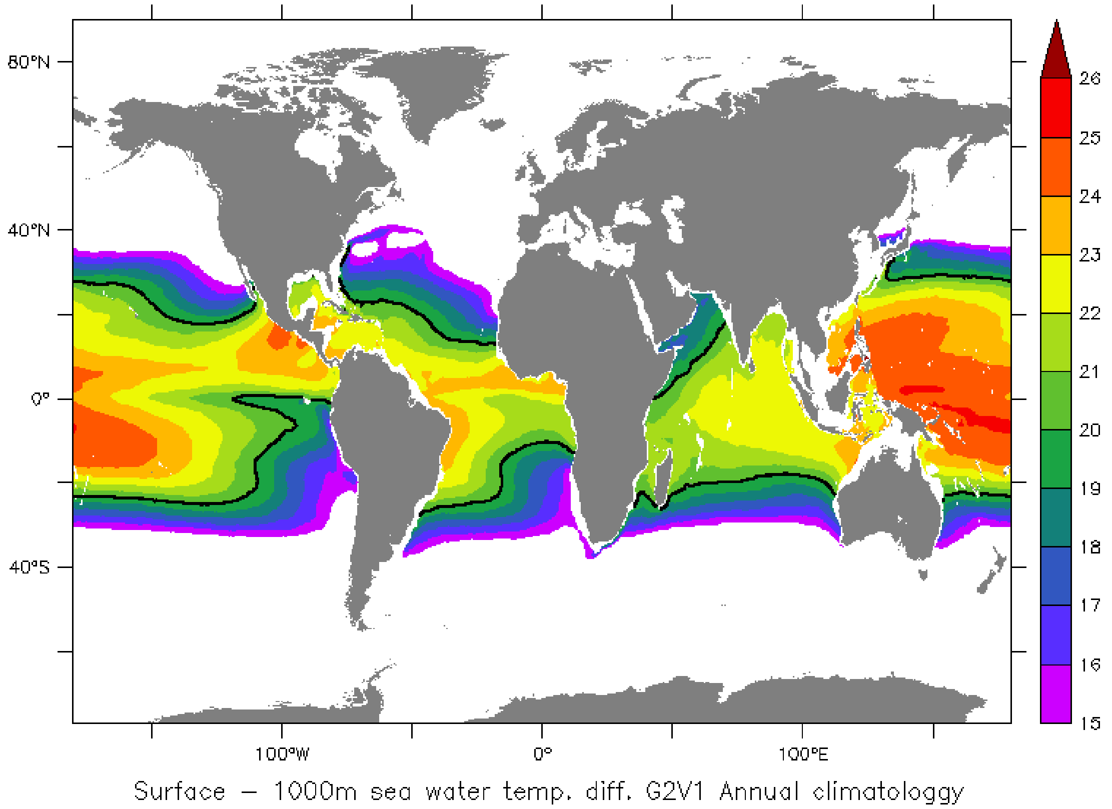

Figure 3-1: From G2V1 annual climatology, temperature difference between surface (first model level between 0 and 1 m depth) and 1000-m depth, colormap in degrees Celsius for temperature differences higher than 15°C. The 20°C isoline is plotted in black.

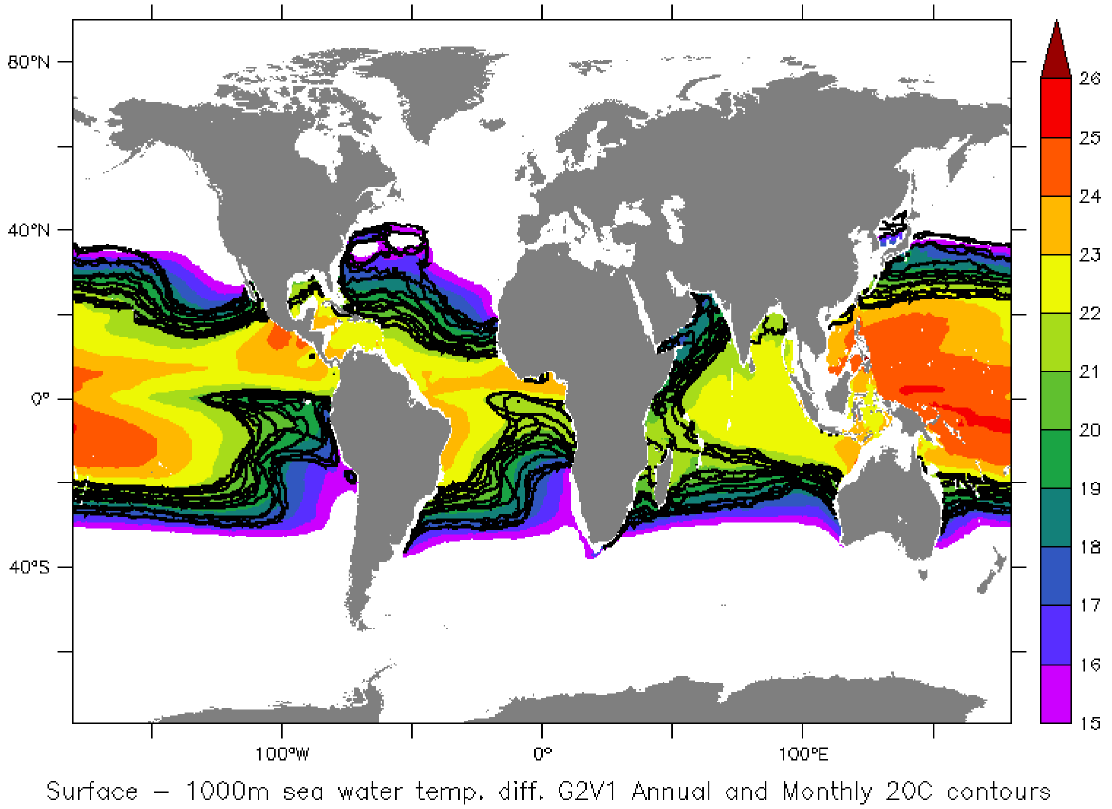

Figure 3-2: like Figure 3-1, but 20°C isolines for the 12 climatological months are overlaid

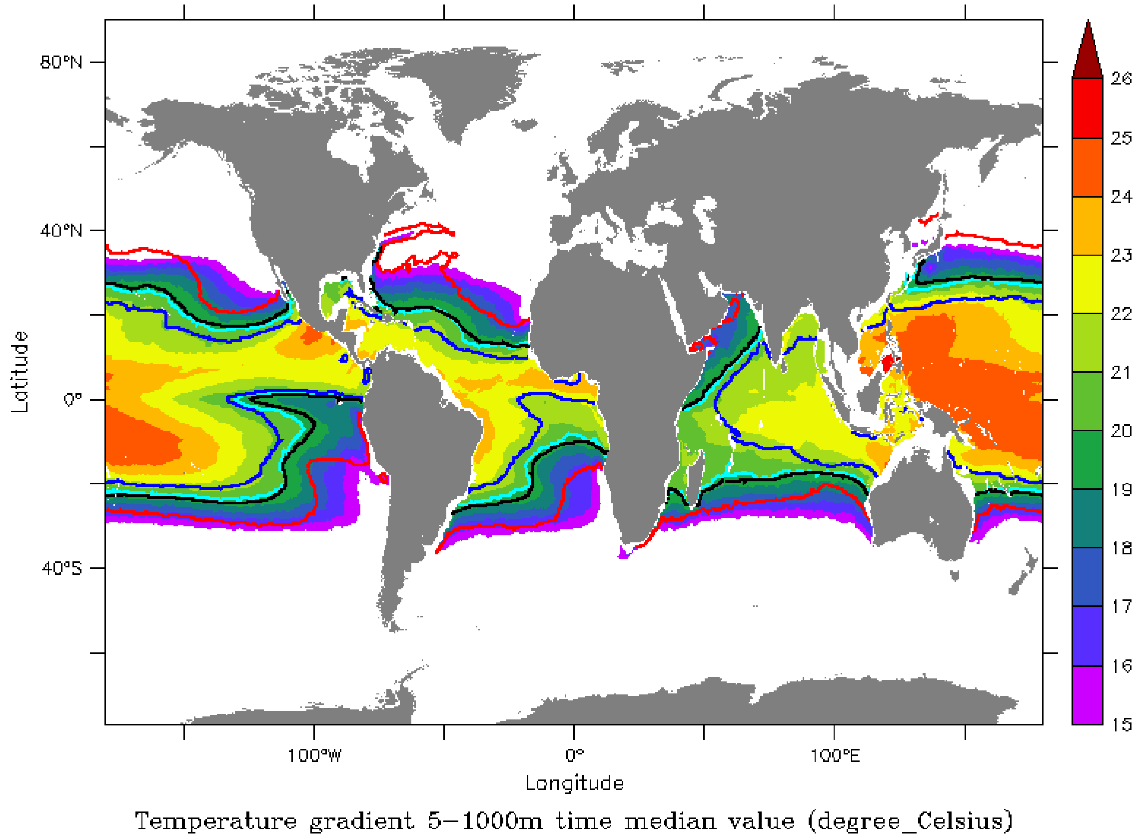

Figure 3-3: From the G2V1 twelve climatological months, mapping of the time distribution of the 5-m to 1000-m-depth temperature difference: shaded is the median value over the 12 months. The 20°C isoline for time mean value, median value, min value and max is plotted respectively in black, cyan, blue and red.

Second question is what shall we consider as "surface" hot water collecting depth? A reference depth of 5-m and 20-m depth was respectively used by [*Chayriguet*, 2010] and [*Nihous*, 2010].

The G2V1 annual climatology is used to plot temperature gradients from surface (first layer of the ocean model, at 0.5-m depth) to 5-m (Figure 3-4) and 20-m depth (Figure 3-5). For the first five meters depth, in our area of interest, limited by the 20°C vertical gradient isoline, temperature differences are negligible.

From surface to 20-m, temperature differences in G2V1 annual climatology are noticeable, and essentially located in eastern side of tropical ocean basins, where shallow mixed layers are expected (Figure 3-6).

Thus the choice of the surface depth of the surface warm water collecting device should be carefully taken into account. If strong dependence on depth is observed in the ocean reanalysis climatology, larger discrepancies could be expected if high frequency atmospheric flux forcing, and vertical mixing (tides, inertial oscillations etc…) are considered.

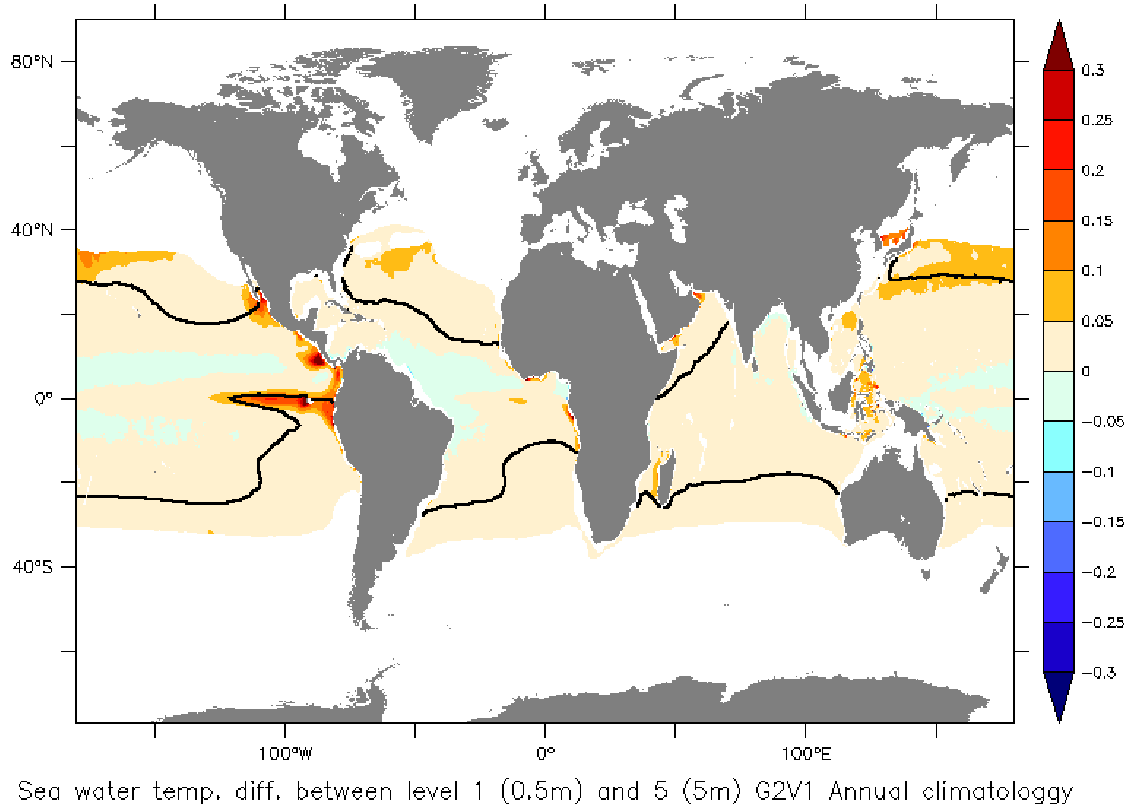

Figure 3-4: From G2V1 annual climatology, temperature difference between surface (first model level between 0 and 1 m depth) and 5-m depth, colormap in degrees Celsius for temperature differences higher than 15°C. The 20°C isoline of the 0-1000-m depth difference is plotted in black.

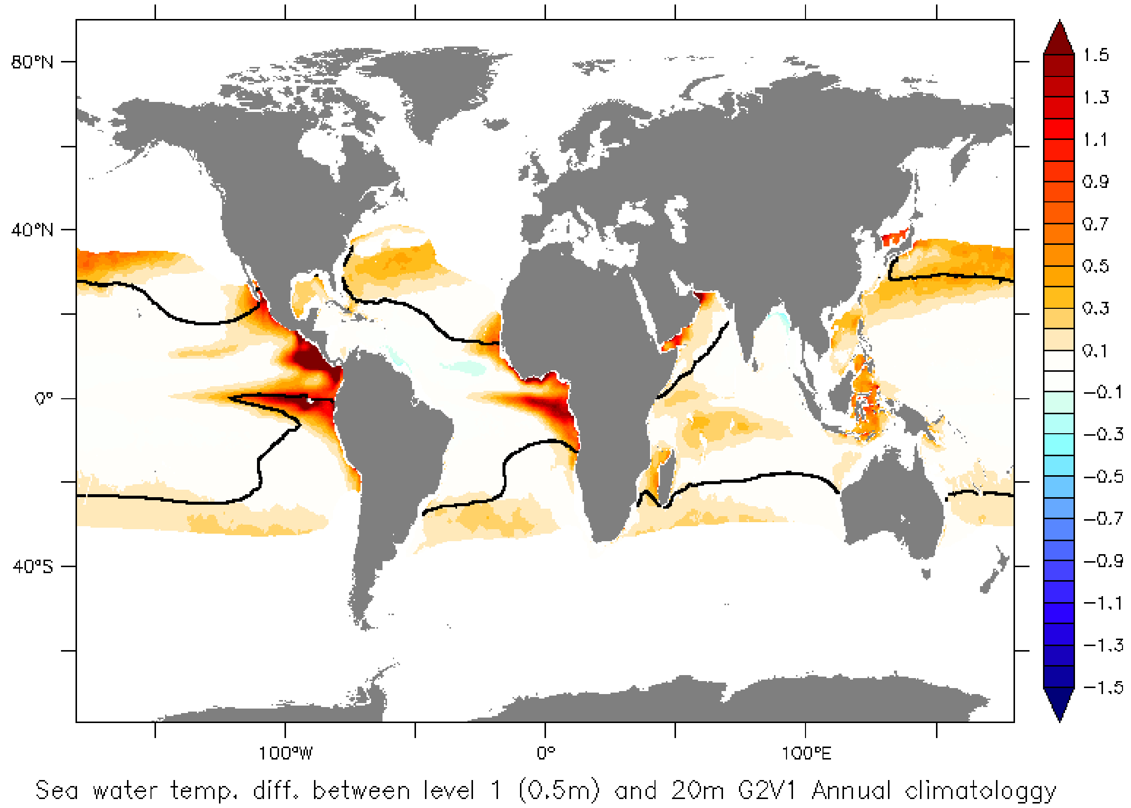

Figure 3-5: From G2V1 annual climatology, temperature difference between surface (first model level between 0 and 1 m depth) and 20-m depth, colormap in degrees Celsius for temperature differences higher than 15°C. The 20°C isoline of the 0-1000-m depth difference is plotted in black.

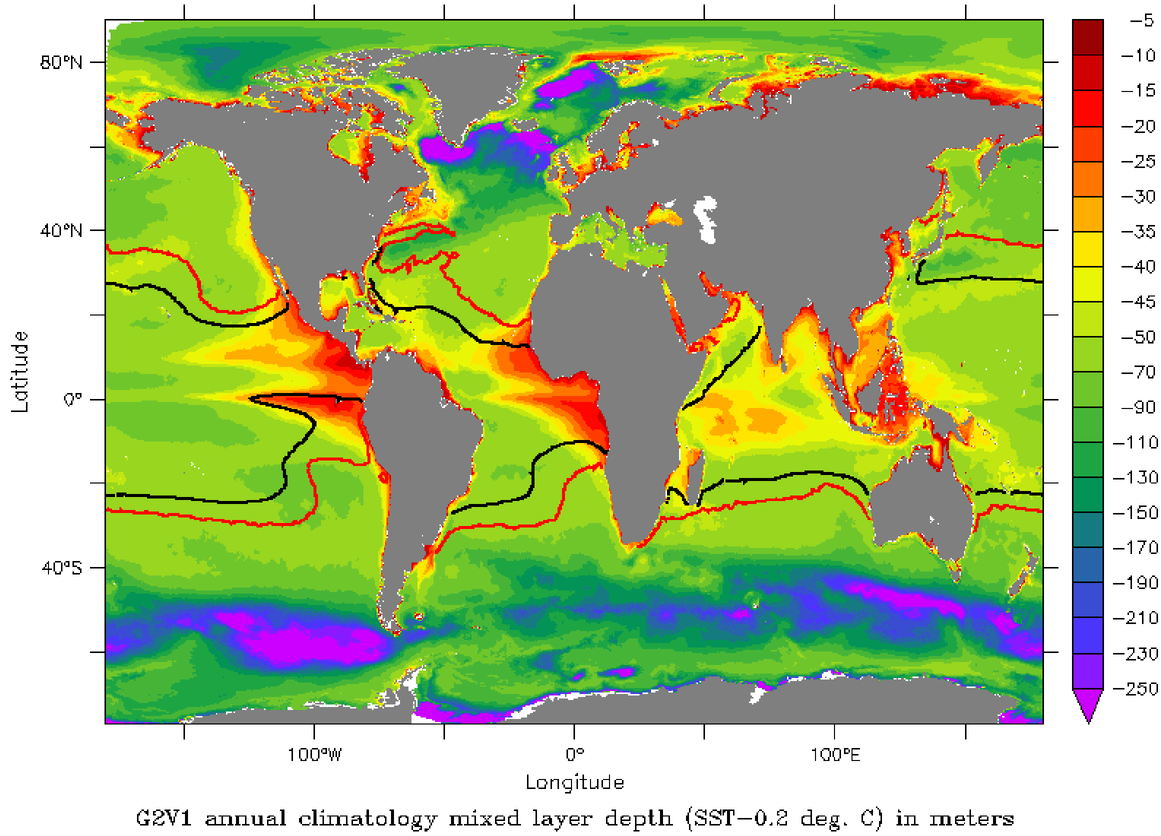

Figure 3-6: G2V1 annual climatology mixed layer depth (in meters): MLD criteria: SST-0.2°C. The red and black isolines correspond to the max and mean area of interest (see Figure 3-3).

3.2.2. The 20°C vertical temperature gradient constraint, and the corresponding depth values

Another way to examine the potential areas is to look at depth for a 20°C vertical gradient. For sake of simplicity, a 5-m depth is chosen for the warm water surface-collecting pipe. Figure 3-7 provides a view of these depths. A similar pattern than for the 20°C criteria and 1000-m-depth constraint is observed. Only tropical areas are matter of interest, and warm-pool and western side of tropical oceans exhibit the shallower depths for this 20°C vertical gradient.

From the G2V1 climatological year, this 1000-m-depth limit for a 20°C vertical gradient appears again with important variability in its distribution (Figure 3-8).

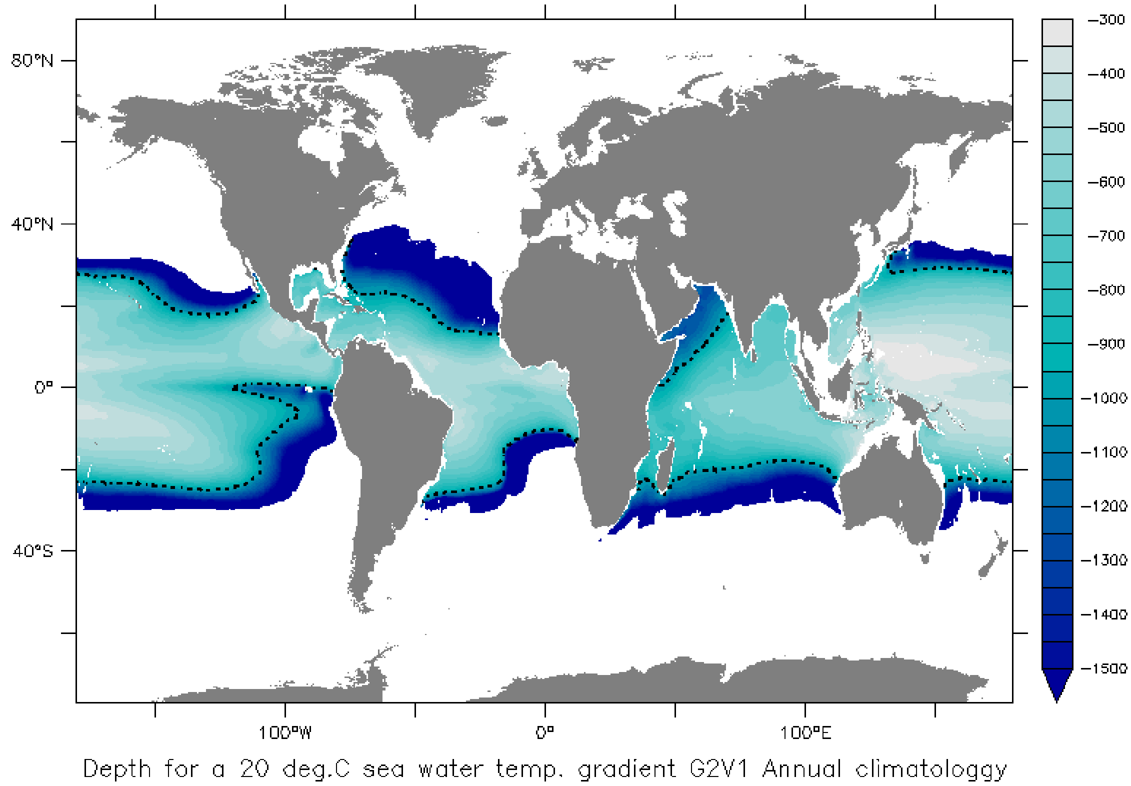

Figure 3-7: From G2V1 annual climatology, depth (in meters) where there is a 20°C gradient from 5-m-depth. The 1000-m-depth isoline is plotted in dashed black line.

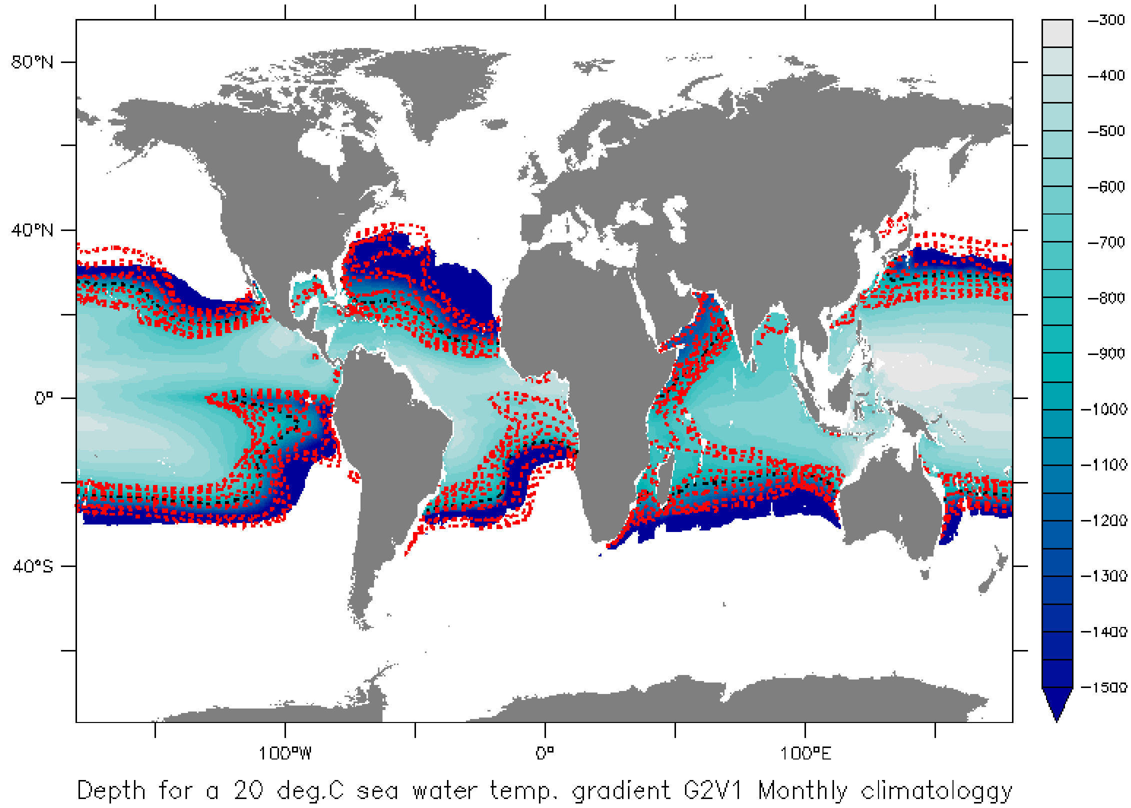

Figure 3-8: From G2V1 annual climatology, depth (in meters) where there is a 20°C gradient from 5-m-depth. The 1000-m-depth isoline is plotted in dashed black line. From the G2V1 monthly climatology red dashed contours correspond to the 1000-m-depth limit.

3.3. Description using the G2V1 monthly averages from 1992 to 2009

Results above show that the seasonal variability has a strong impact on OTEC interesting areas. The interannual variability of the upper ocean thermodynamics, in particular in the tropical areas, might also impact the distribution of interesting areas. In order to better characterize these potential areas for OTEC, the full monthly time series of G2V1 is used, from January 1992 to December 2009 (216 monthly samples). The different aspects to be addressed are:

- What are the temperature changes in the ocean 1000-m top layers?
- Taking the 5-m-depth surface reference, what are the statistics (time variability) for 5-m to 1000-m depth temperature differences?

3.3.1. Temperature changes in the top 1000-m layers

From the 216 G2V1 monthly samples, the temperature standard deviation and variance have been computed for every grid point of the ORCA025 grid (Figure 3-9).

The red isoline delimits the area of interest, following the 20°C criteria max. distribution computed using the G2V1 climatological cycle (Figure 3-3). In this area, from surface to 30-m depth, the ocean temperature standard deviation is low (less than 2°C rms). Only eastern boundaries in the tropical Pacific and Atlantic exceed 3°C rms, due to up-welling activity. At 100-150-m depth, at the thermocline levels, variability can exceeds 3°C rms, in particular in the warm pool areas. Below 500-m depth, the temperature variability is rather low, less than 0.5°C rms in most of the area of interest.

The temperature variability over the 1992-2009 period is summarized in the vertical in Figure 3-10. The temperature variance averaged in the area of interest (as defined above and in Figure 3-3), plotted in red, is lower than the global averaged value in the top 30-m depth. Then below, tropical variability exceeds other areas. Below 500-m depth, variability is lower than 0.5°C rms. It means that –in average- cold water pumping at depth would not be strongly impacted by temperature changes. Always in average, the variance is higher than 1°C rms above 200-m: statistically, it already appears that warm surface water collecting procedure will depend on seasons and depths in many areas.

Another way to illustrate the temperature variability over the 1992-1993 period is given by Figure 3-11. Considering only the area of interest, a space averaging of time-mean, time-minimum and time-maximum temperature is plotted in the vertical. The envelop of variability around the mean is given using the variance plotted in Figure 3-10. Also, from the time-minimum and maximum values of temperature, the minimum and maximum over the area are plotted. Statistically, near the surface, 26°C +/-1.7 is observed, with 23/29°C min/max values. Extremes goes from -1.5 to 33°C. The 300-m depth is a first change in the variability, values are reduced: 12.5°C +/-0.7, with 11/14°C, and extremes between -1.8/21°C. At 1000-m depth, averaged temperature in the area are comprised in 3.5 to 4.5°C range, and extremes between -2/13°C.

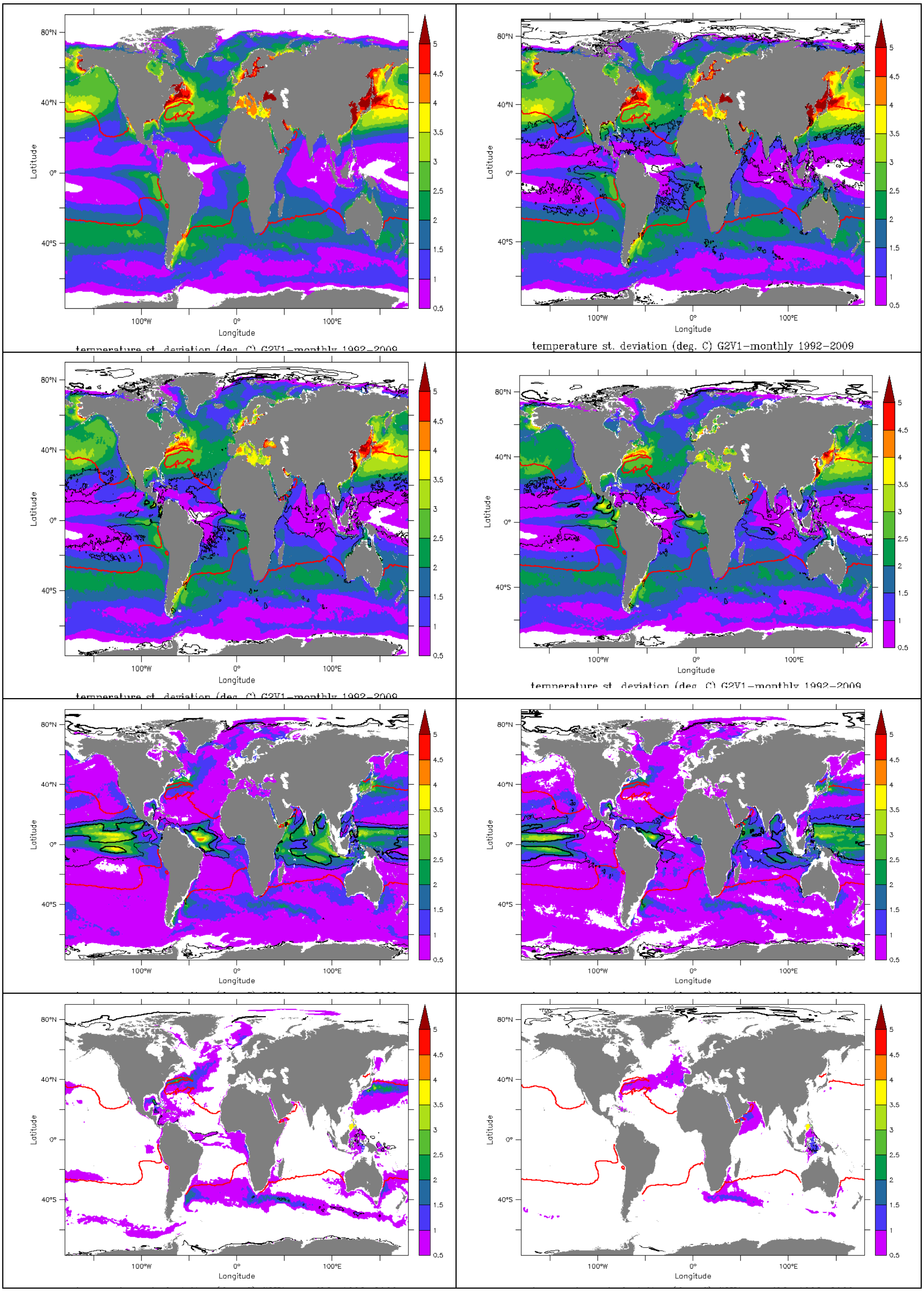

Figure 3-9: G2V1 monthly temperature fields time varying statistics at level 1 (0.5-m, top left), level 5 (5.1-m, top right), level 12 (19.4-m, medium left), level 15 (30.9-m, medium right), level 24 (97-m, medium low, left), level 28 (147.4-m, medium low, right), level 40 (508-m, bottom left), and level 47 (1046-m, bottom right). The time standard deviation (in deg. C rms) is shaded. The Red isoline corresponds to the area where at least one

5-m to 1000-m 20°C difference is observed in the climatological cycle (see Figure 3-3). The thin black isolinecorresponds to variance at that level larger than level 1 variance. The thick black isoline corresponds to variance at that level five times larger than level 1 variance.

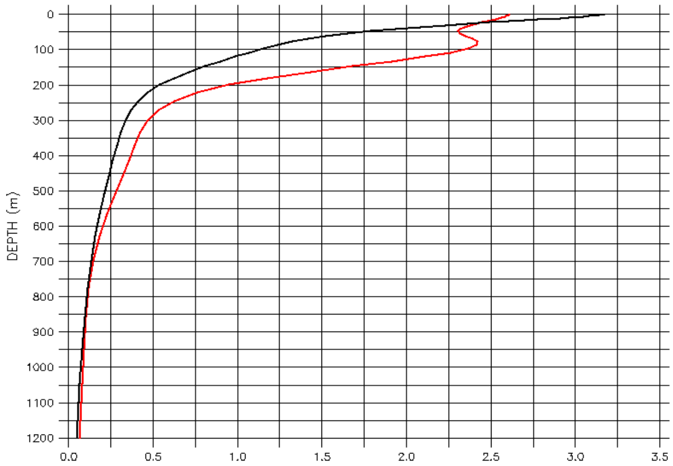

Figure 3-10: From G2V1 monthly temperature fields, time variance, in (deg. C)^2 , on the water column: averaged for the full ocean (black), and only for the area of interest (red) as defined in Figure 3-3 and Figure 3-9.

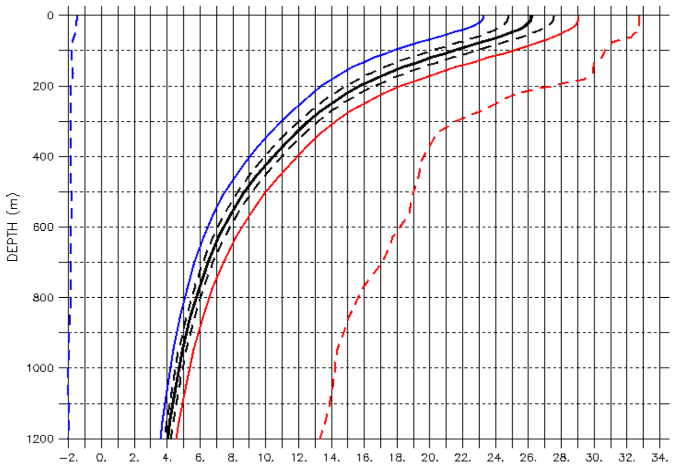

Figure 3-11: From G2V1 monthly temperature fields, statistics in the area of interest as defined in Figure 3-3 and Figure 3-9. Solid black: area mean profile. Dashed black lines: mean profile +/- mean standard deviation averaged in the area. Solid blue line: minimum temperature over time averaged in the area. Dashed blue line: minimum in the area of the minimum temperature over time. Solid red line: maximum temperature over time averaged in the area. Dashed blue line: maximum in the area of the maximum over time.

3.3.2. Statistical analysis of the 5-m to 1000-m temperature difference

For every G2V1 temperature monthly average, the 5-m to 1000-m depth differences have been computed at each location on the ORCA025 grid. From the 216 values of each time series, statistics have been computed: minimum/maximum, mean, median values, then 25-, 68-, 75- and 90-percentiles of each time series.

Figure 3-12 shows a shading of the median value for each distribution. The 20°C isolines of this median field and the mean fields are quasi-juxtaposed, which means that time series at each location offer a distribution close to "normal" or "Gaussian". The red isoline corresponds to the 20°C difference of the fields of maximum values (Figure 3-13, right). It means that over the 216 samples, at least one is equal or larger than 20°C difference. The conservative point of view is given by the 20°C isoline of the field of the minimum values (blue isoline, see also Figure 3-13, left). In this case, all geographical location inside this contour line havethe 216 time samples with difference always larger or equal than 20°C.

Alternatively the engineering point of view could consider the percentile 25 and 68. The percentile 25 indicates the threshold value of the first quarter of the distribution. Thus, looking at the 20°C contour of the geographical distribution of the percentile 25 indicate that every location inside this contour exhibit temperature differences larger than 20°C 75 percent of the time (Figure 3-14). Alternatively, the percentile 68 indicates that locations inside the 20°C contour exhibit temperature difference larger than 20°C only one third of the time (Figure 3-15).

From these statistics, “La Réunion” Island cannot be considered as an optimal area. The “minimum” criteria (contour in blue in figures below) is outside. But the island is close to the percentile-25 20°C contour, meaning that ~75% the water vertical distribution is compliant with the 20°C difference constraint. These results is in agreement with [*Chayriguet*, 2010].

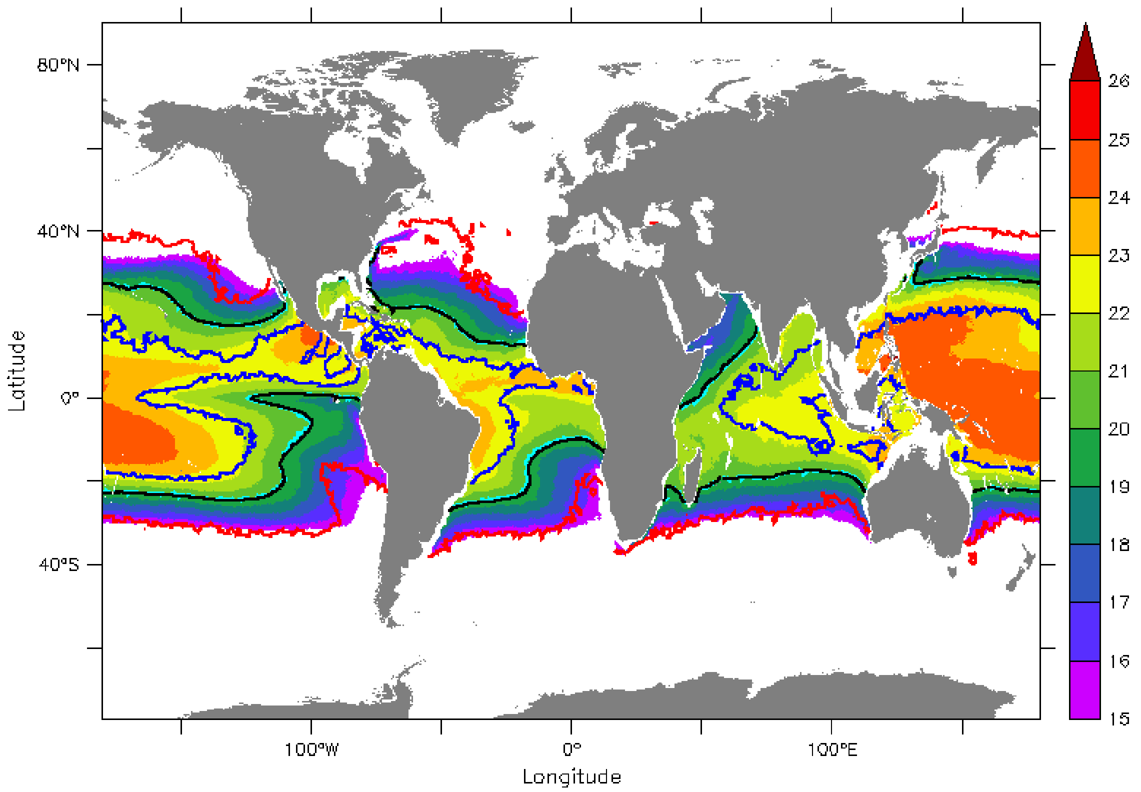

Figure 3-12: From G2V1 temperature monthly averages, computation of the 5-m to 1000-m differences. From time series of differences, plot of the median value for each grid point (in °C). The cyan contour corresponds to the 20°C difference of this median field. The black contour corresponds to the 20°C isoline of the distribution of the time mean value. The blue and red contours correspond respectively to the 20°C isoline of the field of minimum values and the field of maximum values of the time series (see also Figure 3-13).

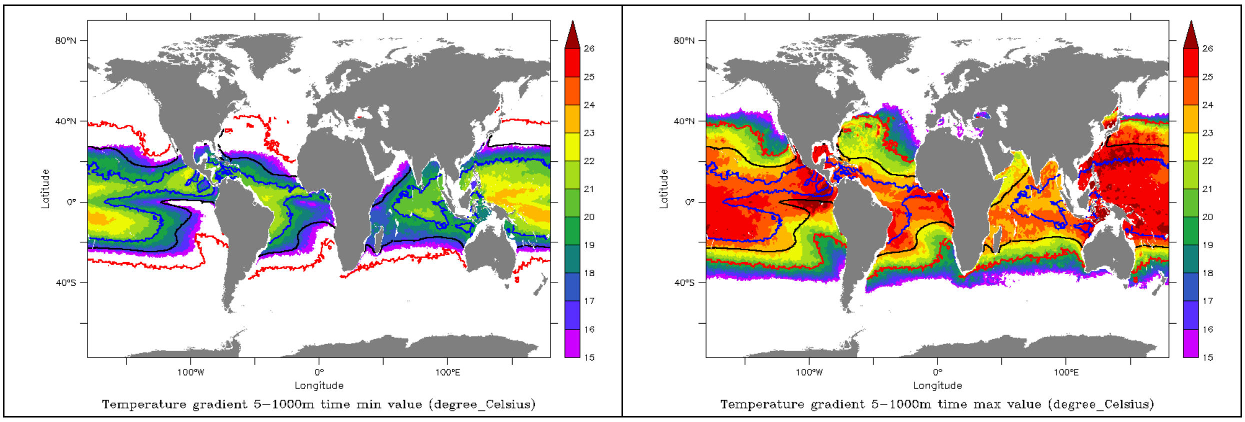

Figure 3-13: From G2V1 temperature monthly averages, computation of the 5-m to 1000-m differences. From time series of differences, plot of the minimum (left) and maximum (right) value for each grid point (in °C). The blue and red contours plotted in both figures correspond respectively to the 20°C isoline of the field of minimum values (left) and the field of maximum values (right) of the time series of temperature differences. The black contour corresponds to the 20°C isoline of the field of the mean value of the time series of temperature difference (see also Figure 3-12).

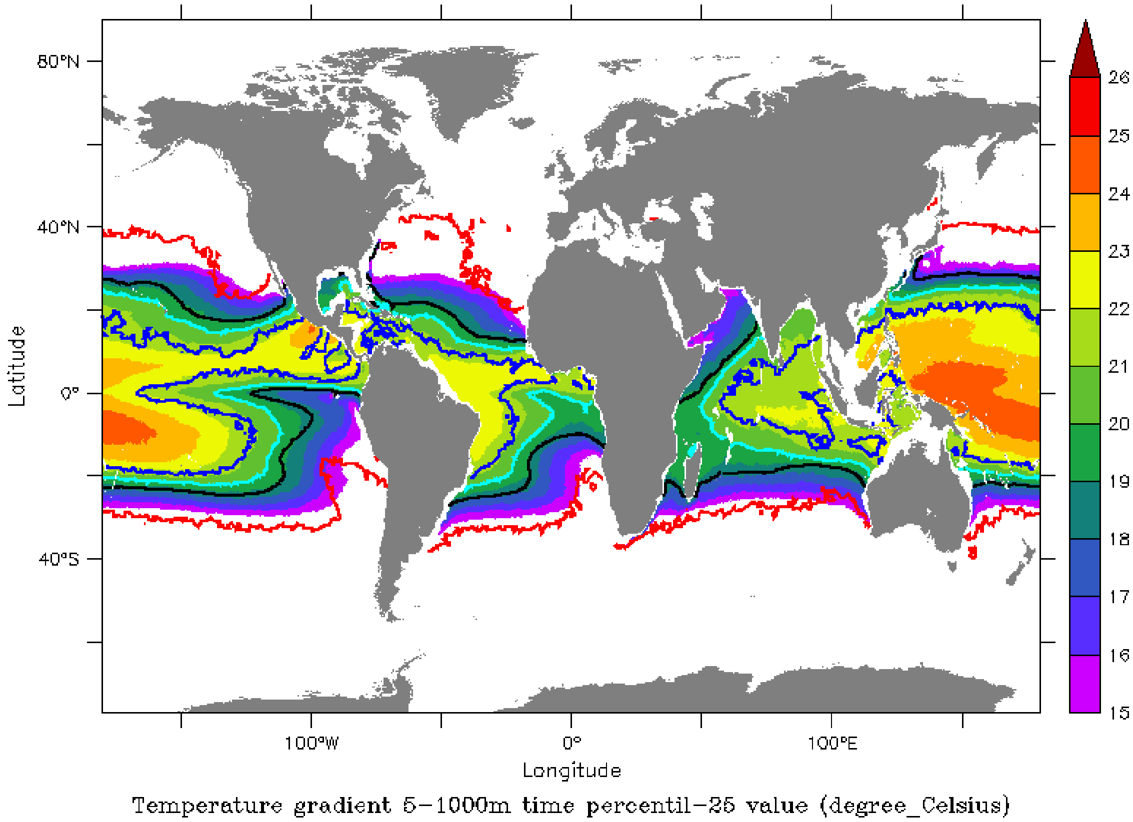

Figure 3-14: From G2V1 temperature monthly averages, computation of the 5-m to 1000-m differences. From time series of differences, plot of the percentile 25 value for each grid point (in °C). The cyan isoline corresponds to the 20°C difference for this percentile. 20°C contour for the maximum (red), minimum (blue) and mean (black) fields are also plotted (see Figure 3-12 and Figure 3-13 for explanations).

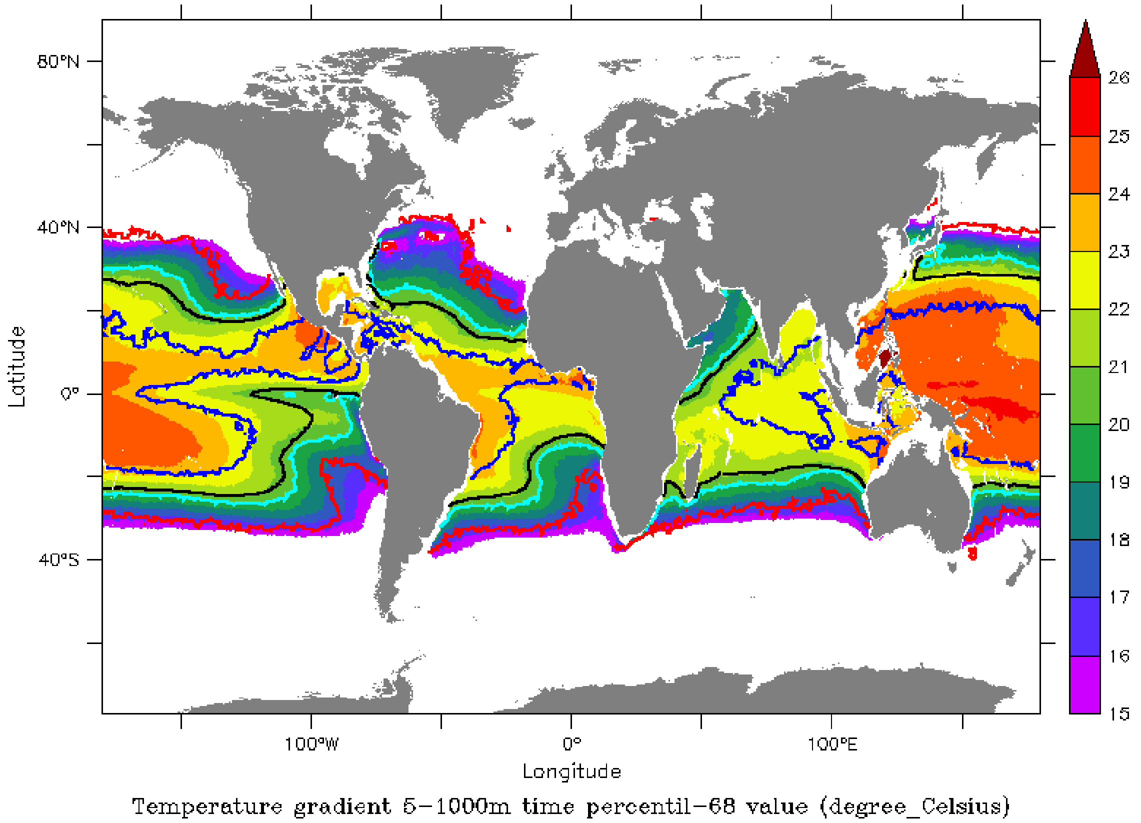

Figure 3-15: From G2V1 temperature monthly averages, computation of the 5-m to 1000-m differences. From time series of differences, plot of the percentile 68value for each grid point (in °C). The cyan isoline corresponds to the 20°C difference for this percentile. 20°C contour for the maximum (red), minimum (blue) and mean (black) fields are also plotted (see Figure 3-12 and Figure 3-13 for explanations).

3.3.3. Statistical analysis of a depth corresponding to a 20°C vertical difference

Similarly to the statistics on the 5-m to 1000-m temperature difference, the 216 G2V1 monthly averages from 1992 to 2009 are used to compute for each point on the ORCA025 grid at which depth a 20°C vertical difference is observed. From the values of each time series on the ORCA025 grid, statistics have been computed: minimum/maximum, mean, median values, then 25-, 68-, 75- and 90-percentiles of each distribution.

In the present depth value computation, bathymetry is a limiting factor, but also time variations in the water masses may limit the number of occurrence of possible depth values corresponding to this 20°C vertical difference.Figure 3-16 shows that the full time series offers possible values in the tropical band, as expected from analysis performed above. Near the coast, on shelves, and on subtropical and eastern side of tropical ocean basins this number drops down. In the analysis below, location where 20% of the samples are missing will be excluded.

Figure 3-17 shows a shading of the depth median values for each time series. The 1000-m depth isoline for the median field is not juxtaposed with the 1000-m depth isoline of the time mean values field. Therefore, pure “normal” or “Gaussian” distribution of depth values is not expected. The minimum depth value distribution (Figure 3-18, left) provides the larger limits of the area of interest. Locations inside the 1000-m depth contour (blue isoline) correspond to places where at least once in the time series a 20°C vertical difference is observed at 1000-m depth. One the other hand, the maximum depth value distribution (Figure 3-18, right) provides the smaller limits of the area of interest. Locations inside the 1000-m depth contour (red isoline) correspond to places where all the time a 20°C or higher vertical difference is observed at 1000-m depth.

Alternatively the engineering point of view could consider the percentile 75 and 25. The percentile 75 indicates the threshold value of the last quarter of the distribution. Thus, the 1000-m depth isoline of the percentile 75 distribution indicates that any point inside this contour correspond to time distribution where 75% of the time depth is lower than 1000-m for a 20°C vertical difference (Figure 3-19). This distribution is rather consistent with the percentile-25 of the 5-m to 1000-m temperature difference distribution (Figure 3-14).Alternatively, the percentile 25 indicates that locations inside the 1000-mdepth contour exhibit depth value for a 20°C vertical difference only one fourth of the time(Figure 3-20).

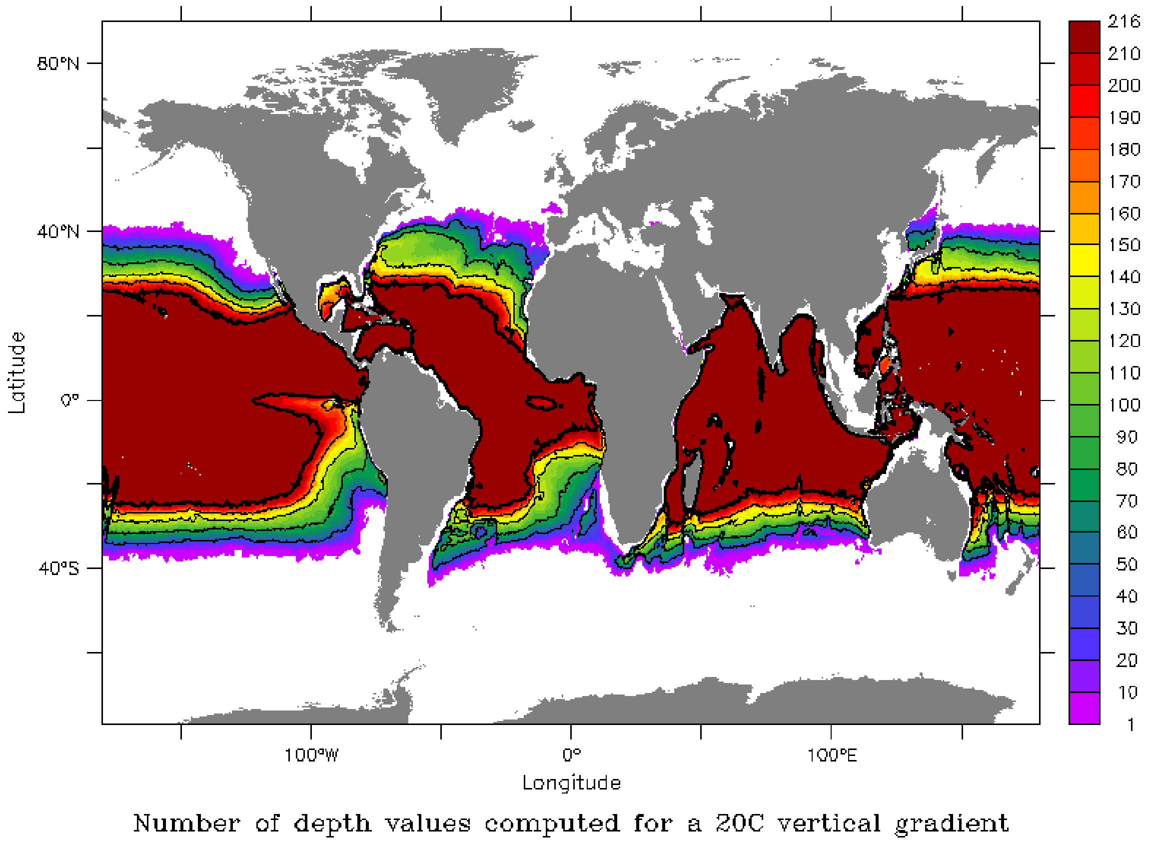

Figure 3-16: Number of occurrence at a given location where a depth is obtained for a 20°C vertical gradient. Black contour every 20% of the total number of samples (216).

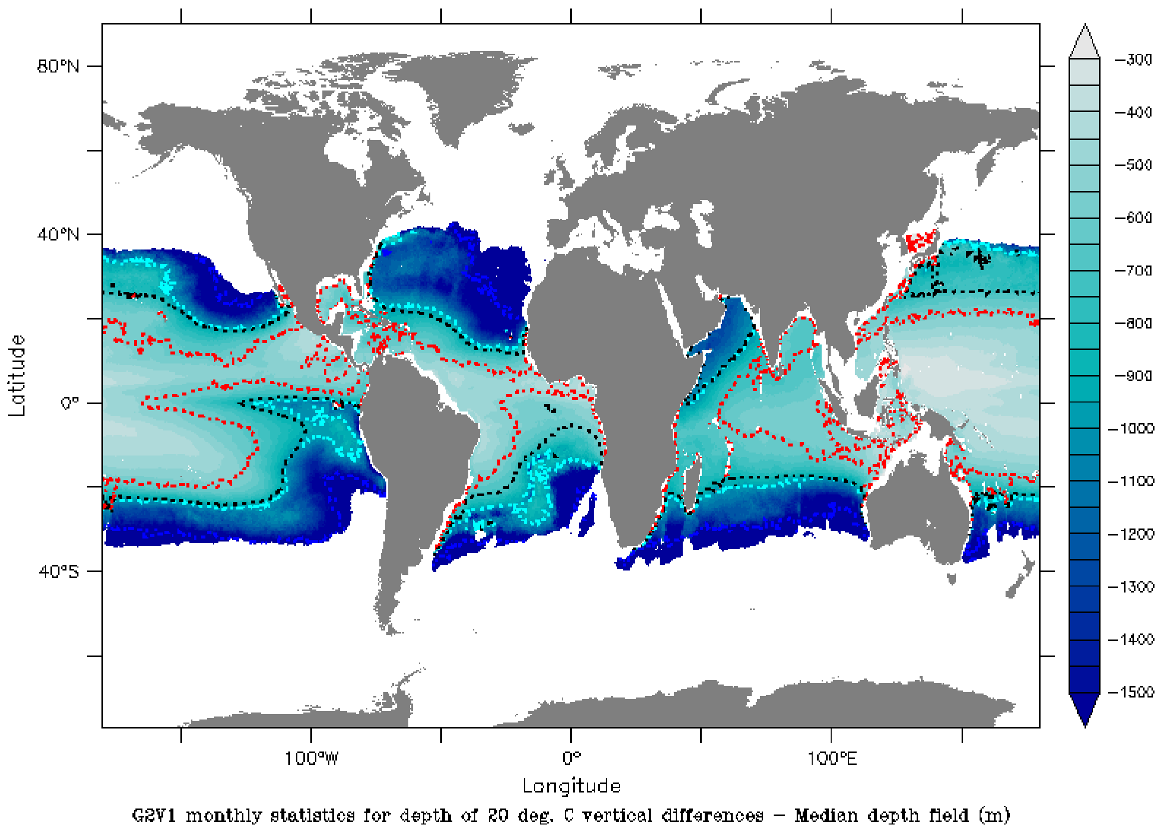

Figure 3-17: From G2V1 temperature monthly averages, computation of the depth of a 20°C vertical difference. From time series of depth values, plot of the median value for each grid point (in meters). The cyan isoline corresponds to 1000-m depth contour of this median field. The black isoline corresponds to the 1000-m depth contour of the distribution of the time mean value. The blue and red isolines correspond respectively to the 1000-m depth contours of the field of minimum values and the field of maximum values of the time series (see also Figure 3-18).

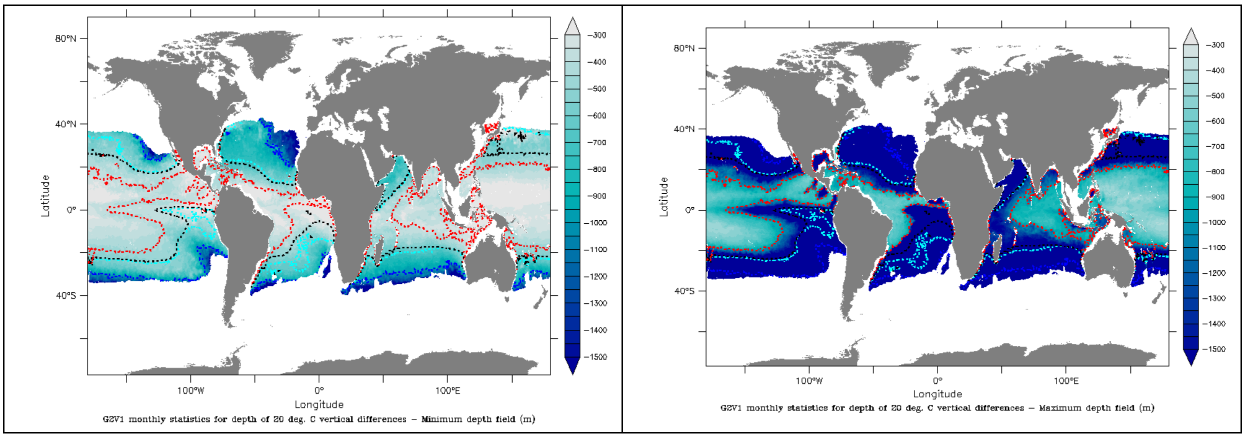

Figure 3-18: From G2V1 temperature monthly averages, computation of the depth of a 20°C vertical difference. From time series of depth values, plot of the minimum (left) and maximum (right) values for each grid point (in meters). The cyan and black isoline corresponds to 1000-m depth contours respectively of the median and mean time distribution fields (see also Figure 3-17). The blue and red isolines correspond respectively to the 1000-m depth contours of the field of minimum values (left) and the field of maximum values (right) of the time series.

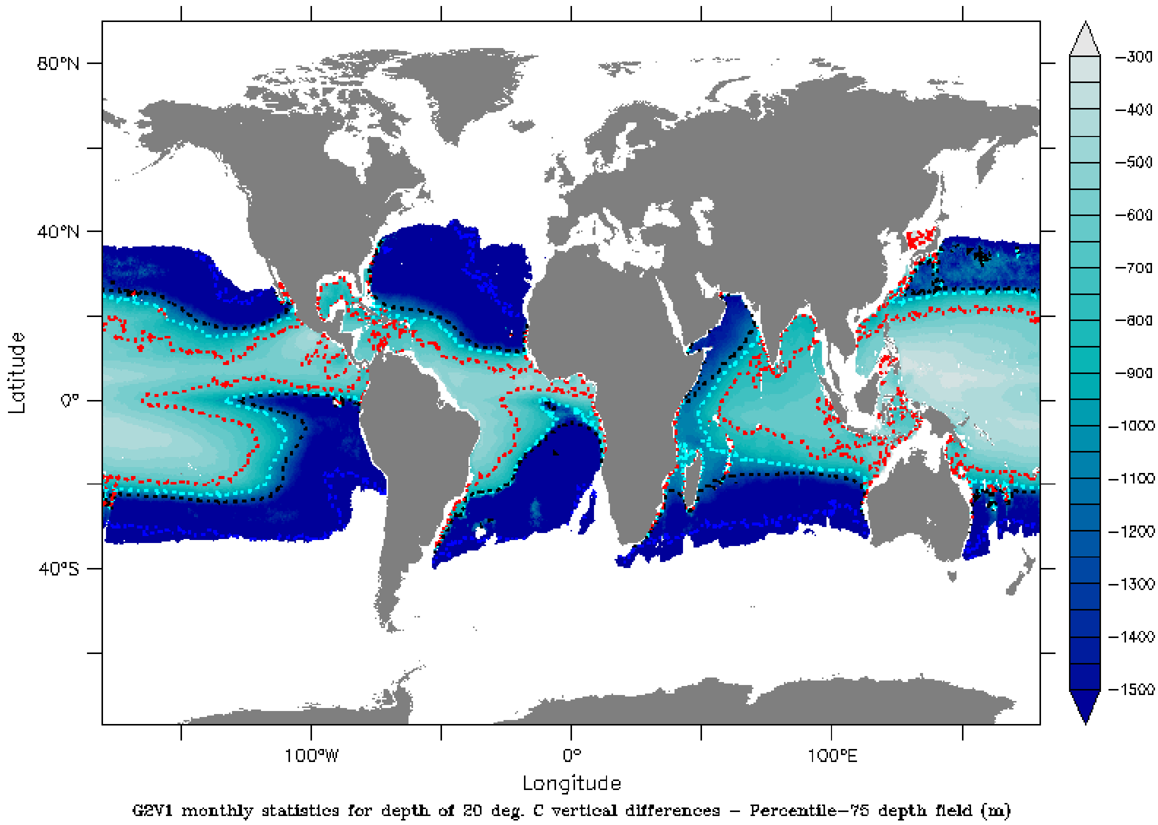

Figure 3-19: From G2V1 temperature monthly averages, computation of the depth of a 20°C vertical difference. From time series of depth values, plot of the percentile-75 value for each grid point (in meters). The cyan isoline corresponds to 1000-m depth contour of this percentile-75 field. The black isoline corresponds to the 1000-m depth contour of the distribution of the time mean value. The blue and red isolines correspond respectively to the 1000-m depth contours of the field of minimum values and the field of maximum values of the time series (see also Figure 3-18).

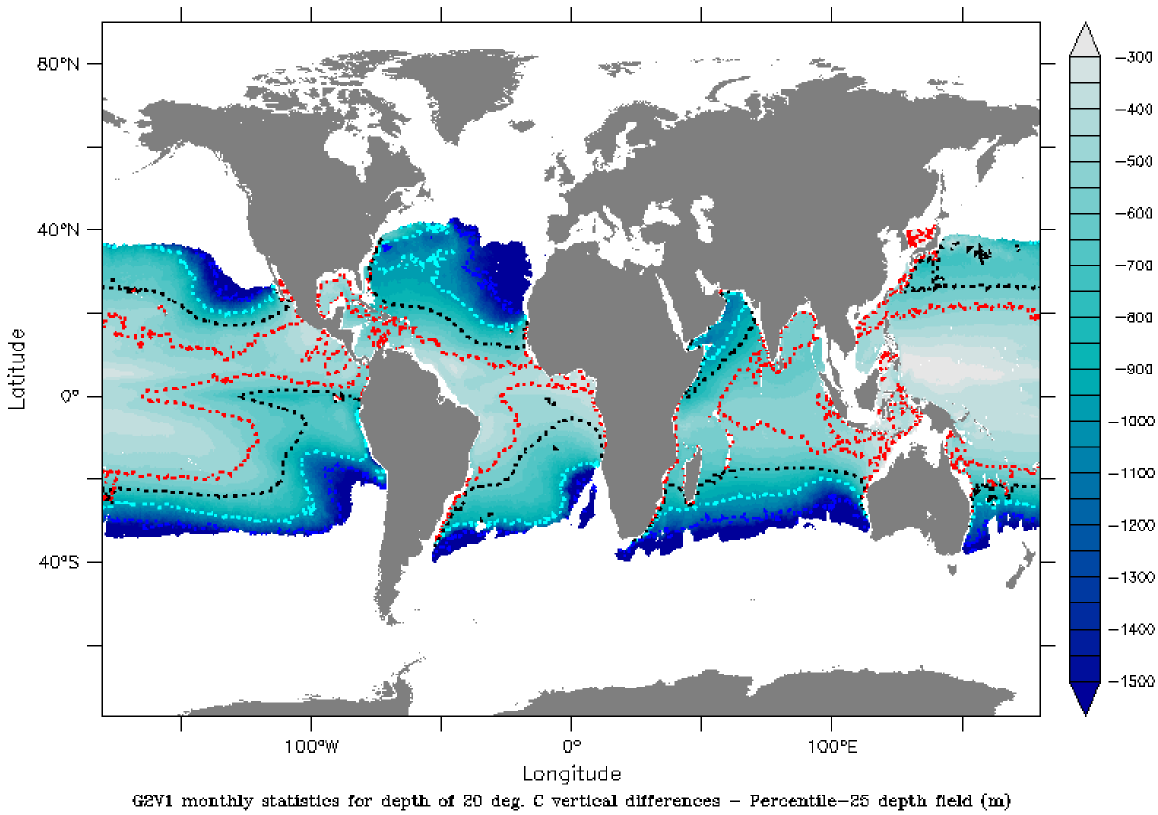

Figure 3-20: From G2V1 temperature monthly averages, computation of the depth of a 20°C vertical difference. From time series of depth values, plot of the percentile-25 value for each grid point (in meters). The cyan isoline corresponds to 1000-m depth contour of this percentile-25 field. The black isoline corresponds to the 1000-m depth contour of the distribution of the time mean value. The blue and red isolines correspond respectively to the 1000-m depth contours of the field of minimum values and the field of maximum values of the time series (see also Figure 3-18).

3.3.4. Synthesis of the two statistics

In order to draw a picture of potential areas for OTEC using the 216 samples of G2V1 monthly averaged temperature, the following cases are proposed:

Most restrictive criteria: the distribution of minimum 5- to 1000-m temperature difference (Figure 3-13, **left), associated with the distribution of the maximum depth limits (**Figure 3-18, **right)**	Low acceptance case: the distribution of percentile-68 of 5- to 1000-m temperature difference (Figure 3-15), associated with the distribution of the percentile-25 depth limits (Figure 3-20)
Highly acceptable case: the distribution of percentile-25 of 5- to 1000-m temperature difference (Figure 3-14), associated with the distribution of the percentile-75 depth limits (Figure 3-19)	*Less restrictive criteria: the distribution of maximum 5- to 1000-m temperature difference (*Figure 3-13*, right), associated with the distribution of the minimum depth limits (*Figure 3-18*, left)*

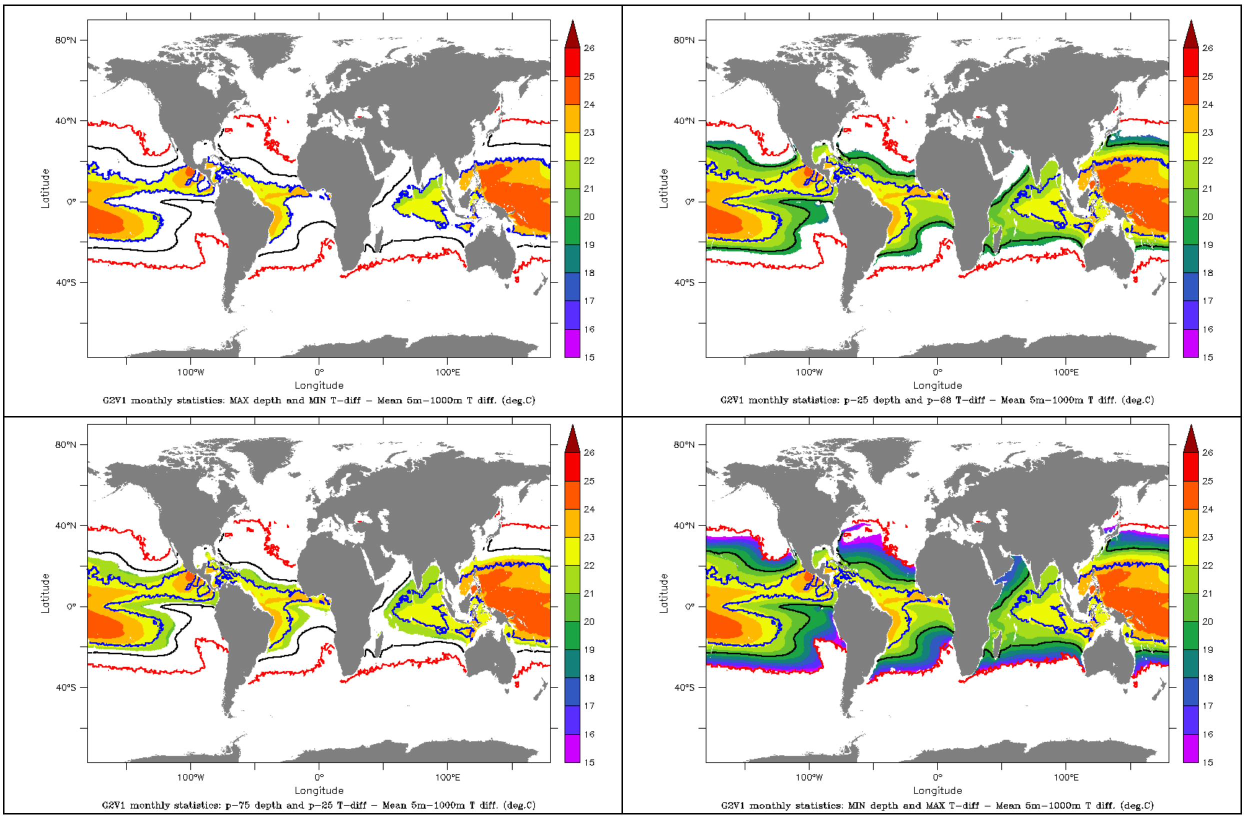

Figure 3-21: From G2V1 temperature monthly averages statistics, four proposed cases (see table above for explanations). The shading corresponds the distribution of the mean value of the 5-m to 1000-m temperature difference. Red, black and blue isoline correspond to the 20°C contour (see Figure 3-12 for details)

4. Conclusion

Blablabla

5. Reference

Chayriguet, A., Caractérisation de la ressource "energie thermique des mers" au large de l'île de la Réunion, Rapport de stage de Master 2 professionel d'Ingénierie Mathématique, *ed. by* Mercator Océan, Ramonville St Agne, pp. 110, 2010.

Nihous, G.C., Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools, *J. Renewable Sustainable Energy*, *2* (4), 043104, 2010.