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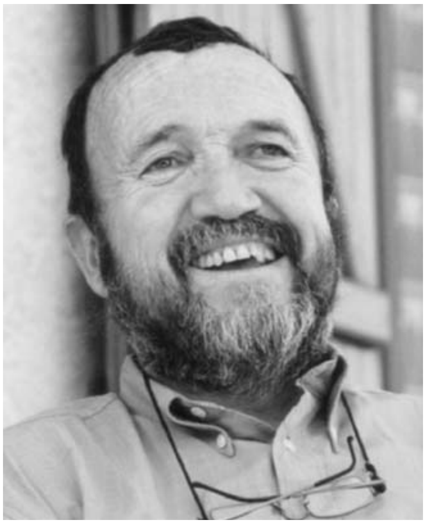
Christian Le Provost on his way



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Abstract This paper is an evocation of the scientific career of Christian Le Provost and of the different research topics in oceanography that have been of interest to him: tides, ocean modeling, altimetry, sea level, tidal dissipation, ...

1 Introduction

I know the sea, and have learned to love it, fear it and respect it right from my childhood days [1]

Since he defended his Ph.D. thesis in 1974, Christian Le Provost (CLP) has been an active participant, both nationally and internationally, in many of the major evolutions that oceanography has known over this period. A large number of oceanographers today have at some time been sailing in the same waters as CLP.

The objective of this paper was to retrace the route that CLP took during his career. This will be done using two texts from Christian himself: one from a lecture he gave in 1998, when he received the Prince Albert of Monaco medal [[1]] and one from his last activity report to the CNRS [[2]]. This latter document in particular provides the skeleton of this overview. CLP dealt with a number of subjects: tides, ocean modeling, satellite oceanography, operational oceanography, sea level, and tidal dissipation. The following sections will address these various topics. In each of Christian's field of interest, we will identify the research situation today and the challenges that remain. This paper is therefore a review of CLP's career: what he wanted to do, what he did, what we did with him, and what we could have done with him. All of CLP's refereed publications are cited.

2 Tides

Let us follow Christian:

After 32 years in research, it is interesting for me to take stock of this period and to ask myself one question in particular: what have been my most significant contributions to my discipline of physical oceanography ? As far as my personal research is concerned, I can answer this question without hesitation: the development of a methodological approach, analytical and numerical, which led to refining a hydrodynamic model of ocean tides on a world scale, a model that the international research community currently considers to be the best in terms of both resolution and precision. Its precision is truly impressive: 3 cm on the principal lunar component! Given the hostility of the ocean environment, any claim to be able to predict, to within a few centimetres, the tidal motion of the free ocean surface at any point in the world requires a certain audacity. Comparison with observations, however, reveals the veracity of this claim [2]

CLP was a man of **ideas** and **methods** and was not afraid to commit himself 100% to research **missions**. Concerning the tides, the two ideas which governed his work were the spectral approach and the choice of a purely hydrodynamic modeling approach. These approaches

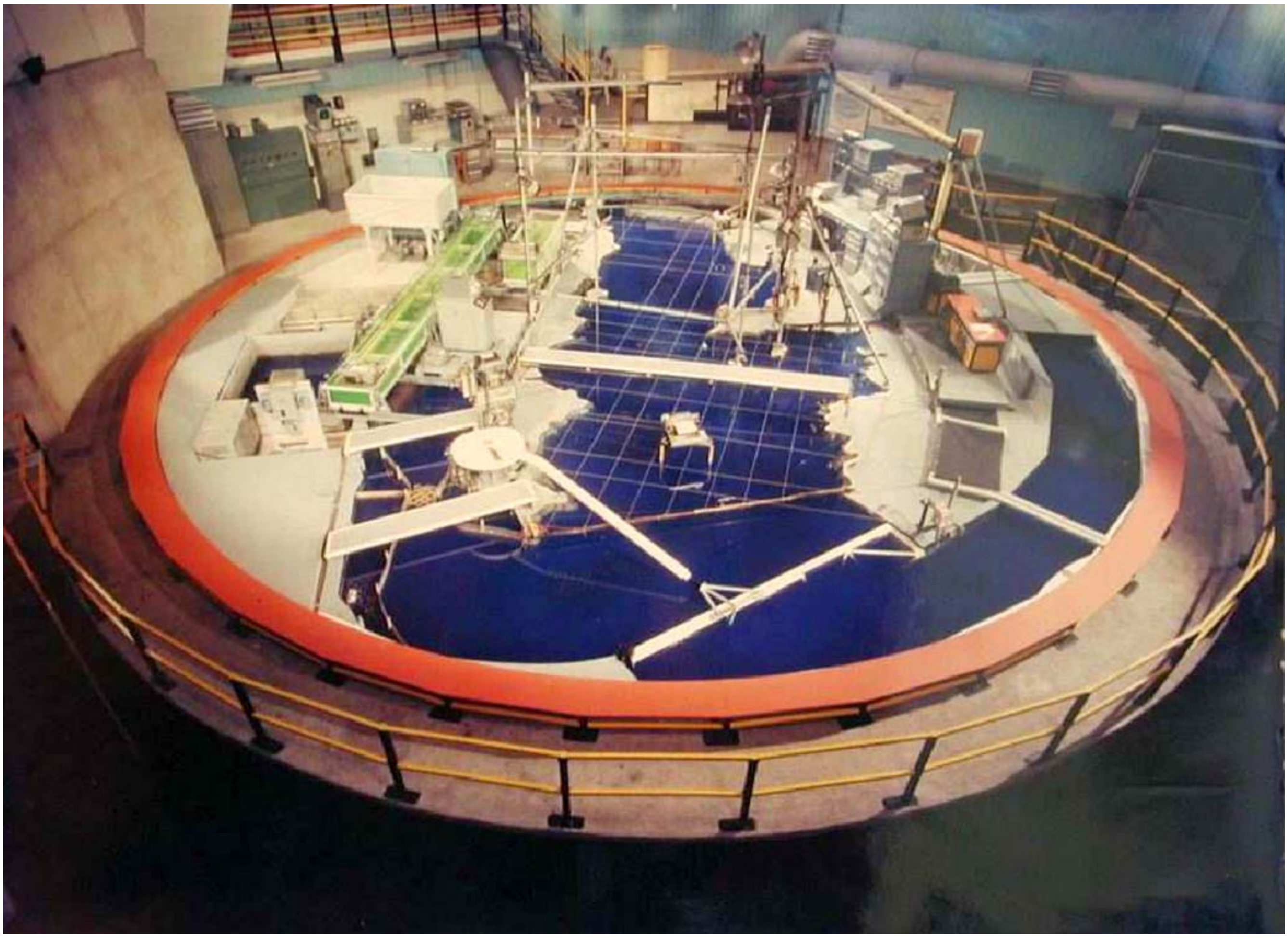

Fig. 1 The Coriolis rotating tank with the Channel scale model

were quite distinct from other methods of an empirical nature, which exist in this field. The CLP tidal methodology encompasses many forms: theoretical, analytical, experimental “in the laboratory”, numerical, and using in situ and satellite observations. It could not have been more diverse. His mission was clearly to understand every possible aspect of the tidal phenomenon.

His work on tides began with his Ph.D. thesis (Le Provost 1974, 1976) where he made complex analytical computations on the harmonic developments of the quadratic friction of the tides (Le Provost 1973a,b; Kravtchenko and Le Provost 1976; Bertrand and Le Provost 1976; Kabbaj and Le Provost 1980). His thesis includes many pages of analytical computations of the various expressions for the nonlinear interaction between the *j* secondary wave and the dominant wave 1 for the various frequencies of the tidal spectrum. This basic hypothesis of the dominant wave for tides is still used today. It naturally leads to a spectral approach for modeling tides (Kravtchenko and Le Provost 1976; Le Provost and Poncet 1977).

The experimental part of this work was carried out at the Coriolis rotating tank in Grenoble (Fig. 1). The Coriolis platform is the largest rotating table in the world and is still a very active scientific tool today. When it was built

Fig. 2 The experimental tide gauge used on the Coriolis rotating tank

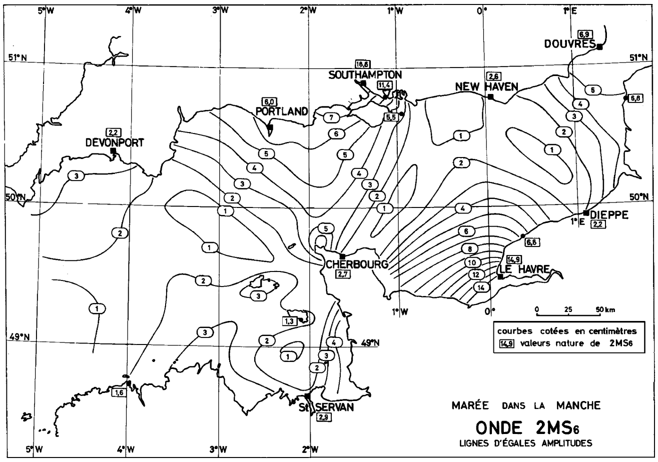

Fig. 3 The 2MS6 harmonic in the English channel

in the late 1950s, the stakes were industrial: a scale model of the English channel was built on the rotating table to study the feasibility of installing a huge tidal power plant in the Bay of Mont St Michel in Brittany (the Chausey Islands project). Is it necessary to remind the reader that CLP originated from Brittany? This had a determining influence on both his career and his life. With CLP, this industrial turntable was raised to the status of a very accurate scientific tool (Chabert d'Hières et al. 1968; Chabert d'Hières and Le Provost 1968). He conducted many measurements that enabled him to produce an atlas of the tides in the English channel. The similitude scales of the Coriolis table are 1/50,000 on the horizontal and 1/500 on the vertical. Thus, 1 cm of actual tide corresponds to approximately 0.02 mm on the Coriolis table.

The experimental tidal gauge used for these measurements was a very simple but very effective system: a pin followed the surface with a vibration system to avoid the effects of capillarity (Fig. 2). Using these measurements, CLP produced the tidal charts for 26 harmonics and subharmonics (Chabert d'Hières and Le Provost 1970–1973b, 1976, 1979). The originality of CLP's work was to apply the results of his analytical study to a physical model of the English channel. This allowed the nonlinear tidal harmonics to be determined very precisely. The example in Fig. 3 shows the 2MS6 harmonic, which is the sixth diurnal tide with a period of approximately 4 h, resulting from the interaction between the dominant lunar semidiurnal M2 tide and the solar semidiurnal S2 tide. In the English channel, the complex nonlinear interactions between the harmonics are strong and contribute in a notable way to the tide's overall signal. As shown in Fig. 3, this harmonic contributes 14 cm near Le Havre, which corresponds almost exactly to the measurement obtained with the physical model. Note that this atlas was used for validating Seasat altimeter data (Le Provost 1981, 1983) and even for the first QuickLooks of Topex/Poseidon in 1992.

CLP's early works focused on exploiting the English channel scale model. But the basic ideas could be transposed to numerical modeling and to any location in the world ocean. CLP developed one of the first 2D numerical models based on the finite-difference technique, with the aim of determining both tidal elevations and tidal currents for the main constituents (Le Provost and Fornerino 1985; Fornerino and Le Provost 1985; Molines et al. 1989). The computing capabilities were very limited at that time, and the model predictions were rather poor: the accuracy of the numerical model was clearly less than that of the physical model (at least for tidal elevation).

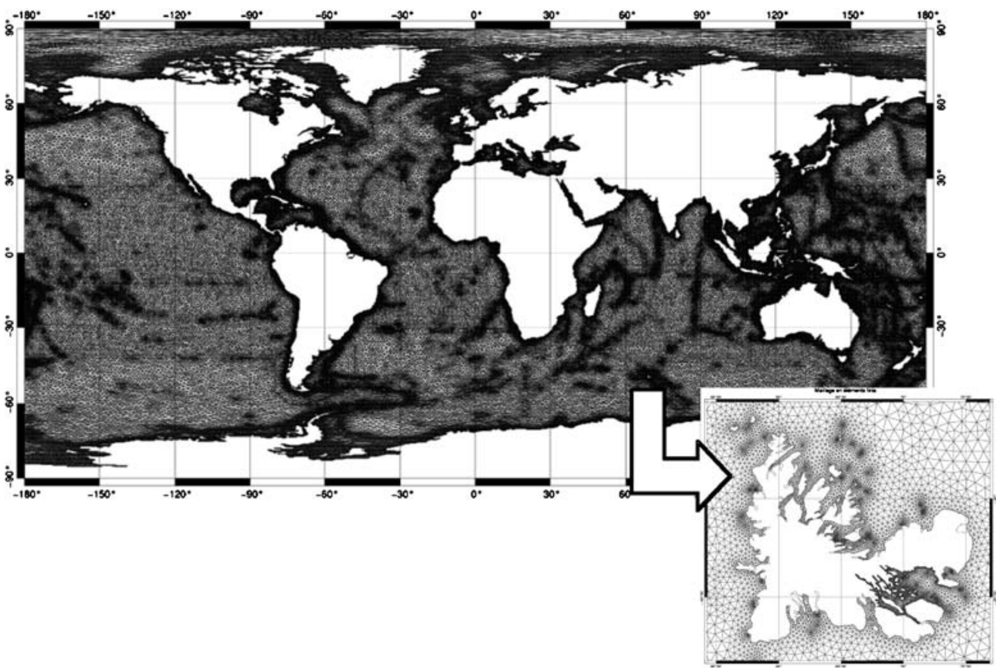

Fig. 4 The finite element grid of the FES model over the global ocean. A zoom over the Kerguelen island shows fine details

The spectral approach used by CLP in his thesis transforms the hyperbolic problem (longitude, latitude, and time) into an elliptical problem (longitude and latitude) for each component of the spectrum. By avoiding the time integration, the elliptical formulation is much less costly. In addition, because the elliptical problem allows a variational formulation, the most natural numerical choice of numerical method is the finite-element method which enables complex refinement in any geographical location (Fig. 4).

Many people worked with CLP over a number of years on the development of the CEFMO model and its FES solutions (Le Provost and Vincent 1986; Vincent and Le Provost 1988; Le Provost et al. 1991, 1994a, 1998; Le Provost and Lyard 1993, 1997; Genco et al. 1994; Lyard and Le Provost 1997; Arnault and Le Provost 1997; Lefèvre et al. 2000a,b, 2002). First, the basic concepts of the model were defined (with the major ingredients as indicated in this study). Subsequent improvements were carried out through basin studies and eventually with a global model of very high resolution and the assimilation of data. By the way, the finite element approach always aroused CLP's interest. It was the starting point for a fruitful cooperation with applied mathematicians, particularly in Grenoble (Le Provost and Poncet 1977, 1978; Le Provost et al. 1981). Several years later, CLP considered using this finite element approach for ocean models, with applications for the midlatitudes (Le Provost et al. 1994b). Although the finite-element technique has not yet been adopted as a standard technique for ocean circulation modeling, it does have a promising future.

We have all seen these global cotidal charts (Fig. 5) which provide information on both the amplitude and the phase of the tides. The first chart corresponds to the M2 tidal amplitude and the second to the M2 tidal phase, obtained from the latest FES2004 solution.

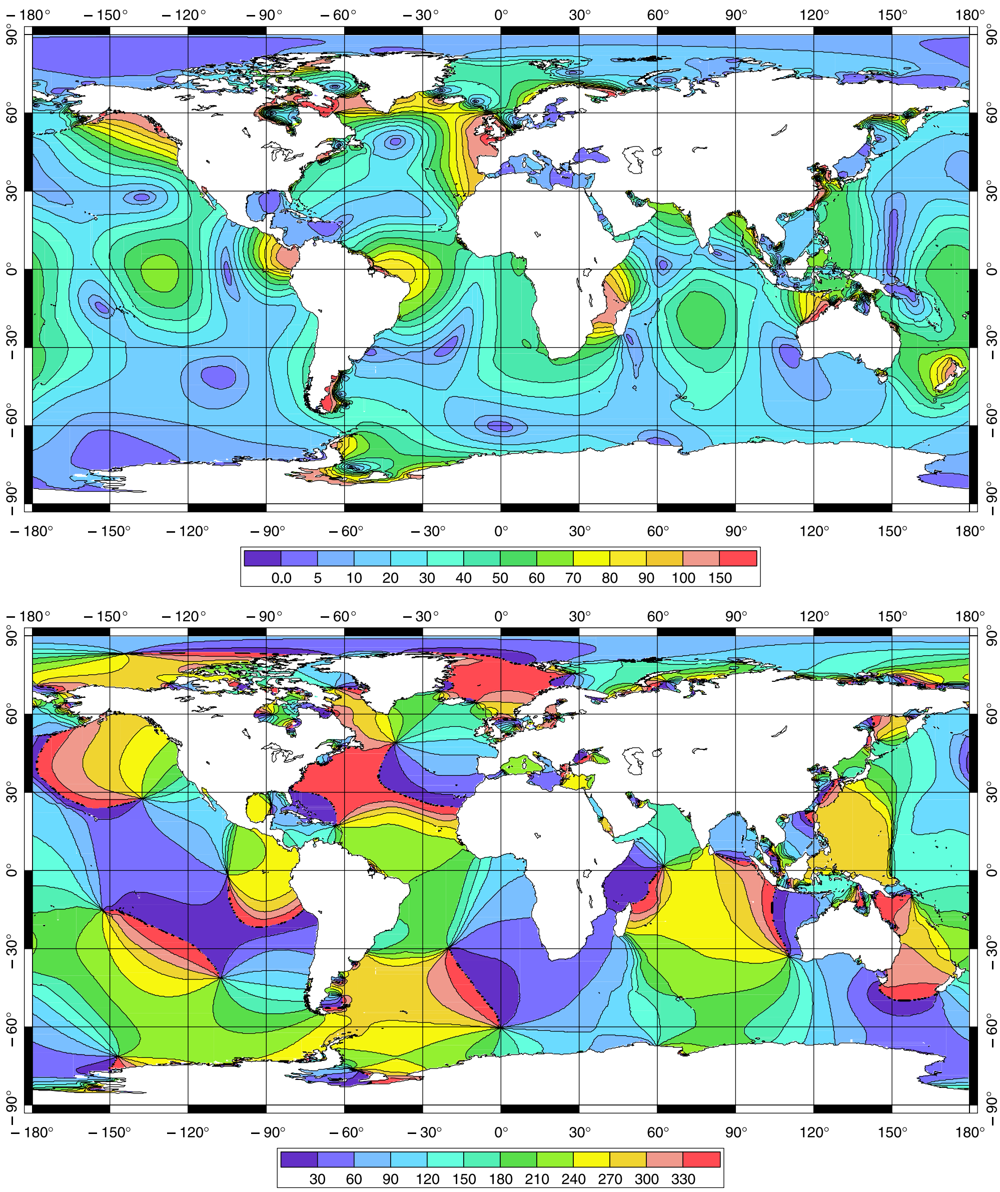

Fig. 5 M2 tidal amplitude and phase over the world ocean

> *It is undoubtedly due to my childhood years in Brittany with its marine environment that I feel this constant need to compare my theoretical results with observations from the real world* [1]

CLP liked to refer to Brittany. He was clearly motivated throughout his life to that the results of his theoretical and modeling work be compared against observations.

By comparing the models to observations, we can chart the progress in open-ocean tidal predictions, and the results are spectacular. Starting from 1980, the year of the first tidal model of Schwiderski, up to today, progress has been considerable as seen in Fig. 6. Today, the global tides are known with an excellent level of precision as mentioned previously by CLP. However, there are still significant problems in rather specific locations where the error remains greater than 1 m. The bottom maps in Fig. 6 clearly show the location of these errors and their regional character, often associated with shallow seas and the presence of shelves: the Patagonian plateau, North–East Europe, Indonesia, etc.

Figure 7 shows a summary of the evolution of the models' performances over the world oceans in comparison with the measurements obtained from deep tide gauges (Shum et al. 1997). This graph shows a mixture of predictions based on an empirical approach (i.e., a direct data analysis of the satellite altimetry data) or based on hydrodynamic modeling and data assimilation.

In the domain of tidal research, many of the major questions regarding global ocean tides have been answered. For example, during the 1980s and 1990s, the tidal modeling community was asked to provide precise tidal corrections to improve the precision of satellite altimetry data. This request has now been met for the main astronomical constituents. Remaining issues concern the long-period radiational tides, internal tides, and more

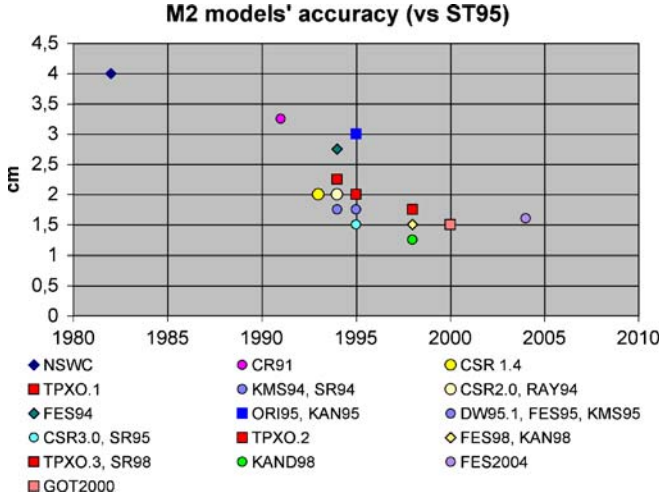

Fig. 7 Accuracy of the global M2 tide measured by the complex misfit between tide gauge data (ST95) and the global M2 model solutions: hydrodynamic models with partial tide gauge assimilation (NSWC, FES94, FES98), hydrodynamic models with full assimilation (FES95/99/2004, TPXO1/2/3, KAN95/98, ORI95), and empirical models (CR91, CSR1/2/3, SR95/98, KMS94/95, RAY94, DW95, GOT00)

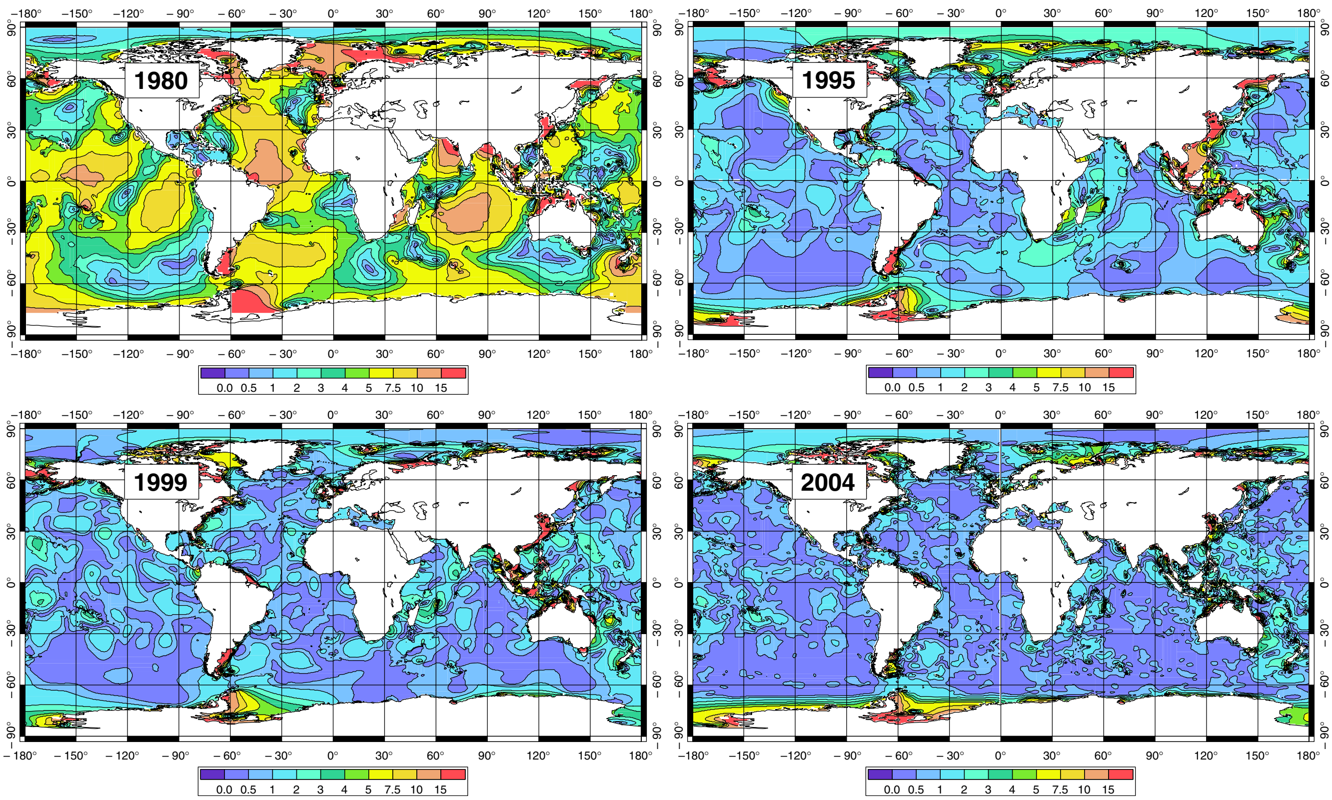

Fig. 6 Tides accuracy for the M2 component ias computed by CLP models in years 1980, 1995, 1999 and 2004

generally nonlinear tides. But perhaps more importantly, the regional seas pose specific challenges:

- In the presence of topography, nonlinearities induce residual circulations which are poorly known, and topographic trapped waves can interact with tides in a complex manner.
- Methodological and technical problems also exist at the local scale: specific data assimilation issues, poor knowledge of the bathymetry, and unknown observation errors.

Tidal models need to be improved locally, and perhaps, more importantly, the connection between local and global models warrants further research.

3 Ocean modeling

With regard to scientific collaboration at the national level, I believe I have contributed to the development of a French community of numerical ocean modellers, which has now achieved international status. The Grenoble "tide and ocean modelling" team, which I created and supervised until the end of 1996, has thus acquired European and international renown, not only in the area of tides, but also in general ocean circulation numerical modelling, and in particular the assimilation of satellite altimeter data into its models [2]

When he started working on numerical ocean modeling, CLP had two major **ideas**: firstly, to evaluate the role of mesoscale eddies on the general ocean circulation, the importance of which have already been suspected by W. R. Holland in particular; and secondly, to evaluate the role of topography in the ocean circulation, the generation of eddies, the current stability, and the interactions with oceanic turbulence. The **tool** was numerical modeling. The ultimate objective was to make modeling realistic, even though, in the beginning, the working ocean model was rather crude. CLP's **mission** was to create a French community of ocean modelers at an international standard.

They started with a "square ocean" which was already familiar to the US community (Fig. 8). With this very simple configuration, CLP and his team were able to contribute to the understanding of the importance of eddies and oceanic turbulence, the way eddies interact with the mean flow, and how, in fact, oceanic turbulence builds the average current. The current in the middle of the box ocean is supposed to mimic strong currents such as the Gulf Stream or the Kuroshio. Surprisingly, actual Gulf Stream eddy statistics are fairly close to the eddy statistics in such a simple box model (Le Provost and Verron 1987; Barnier et al. 1989, 1991; Verron and Le Provost 1991; Blayo and Le Provost 1993). The first computer available, a Cray1, had to work hard to complete these calculations.

Since 1982, more background work has been carried out on topographic effects, with process models in all kinds of

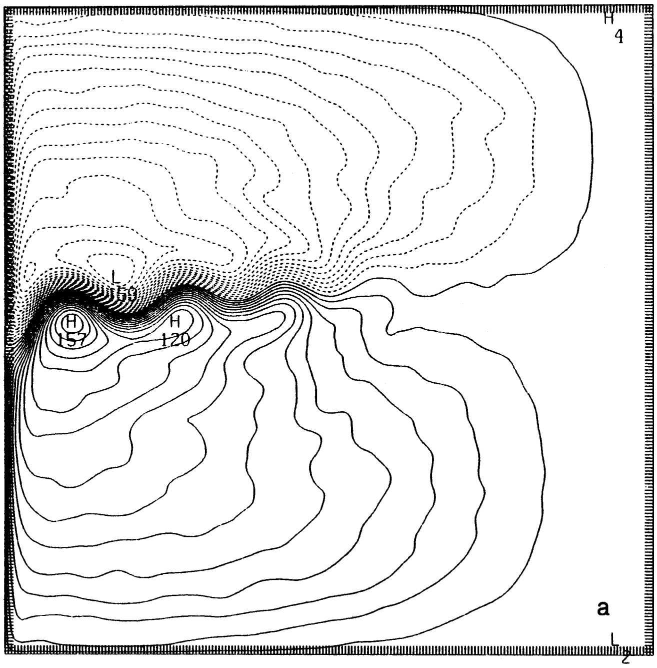

Fig. 8 Ocean circulation box model used for process studies of midlatitude inertial jets such as the Gulf Stream

configurations: isolated seamounts (Verron and Le Provost 1985), underwater ridges (Verron et al. 1987), topographic roughness (Barnier and Le Provost 1993), capes, canyons, etc. (Fig. 9). The richness of the subject is enormous, and there are still a lot of things to do and to understand today in this respect. Indeed, realistic large-scale modeling often needs to be fed by specific process studies. Adequately, forcing of the oceans is also a key issue (Mac Veigh et al. 1987).

The transition to primitive equation modeling, considered in particular during the DYNAMO project, was accompanied by significant questions on the choice of the vertical coordinates. The choice was strongly governed by the need to adequately represent the effects of topography. The DYNAMO project was also exemplary with respect to its European interlaboratory character (Killworth et al. 2001; Willebrand et al. 2001). The project's major objective was to compare the general ocean circulation produced by models which differed only in their vertical coordinates. The results were not simple. The relative efficiency of the coordinate system varies according to the regions and the local physics. The universal miracle coordinate system does not exist, and perhaps hybrid coordinates are the solution. During DYNAMO, the Cray98 computer was brought to its knees.

The CLIPPER project marks another important stage with its deliberate willingness to compare model results with observations. The CLIPPER modeling project was designed to supplement the field program carried out during WOCE (hydrography, floats, and moorings). It simulated the WOCE years (1980–2000) with a $1/6^o$ high-resolution model of the Atlantic. The level of realism of the model allowed direct comparisons between the model velocities and the WOCE current meter database (Fig. 10).

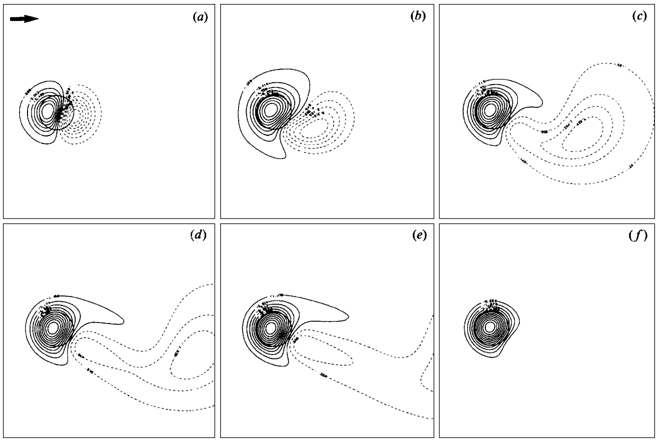

Fig. 9 Eddy generation by a uniform current over and within the lee of an isolated seamount

The T3E computer was more than overworked for this experiment.

Today, global coverage has been reached with the Drakkar project (Fig. 11). The objective of this project is to understand the mechanisms governing the variability in the North Atlantic and the Nordic Seas and to discriminate between sources of variability: local or remote, intrinsic or atmospherically forced. A global model with sea ice is integrated at eddy-permitting resolution (1/4^o) over 50 years. Figure 11 from the Drakkar numerical simulations shows the variations in dynamic topography over a 5-year period. As can be seen, the ice extension is also taken into account in the model.

The **challenges** in oceanic modeling today relate to:

– Our capacity to build a dynamic framework for interdisciplinary studies such as coupling sea ice, biology, and biogeochemistry.
– Model improvements are certainly still on the agenda with the aim of reducing the model biases and enhancing the forecasting skills. However, we are at an

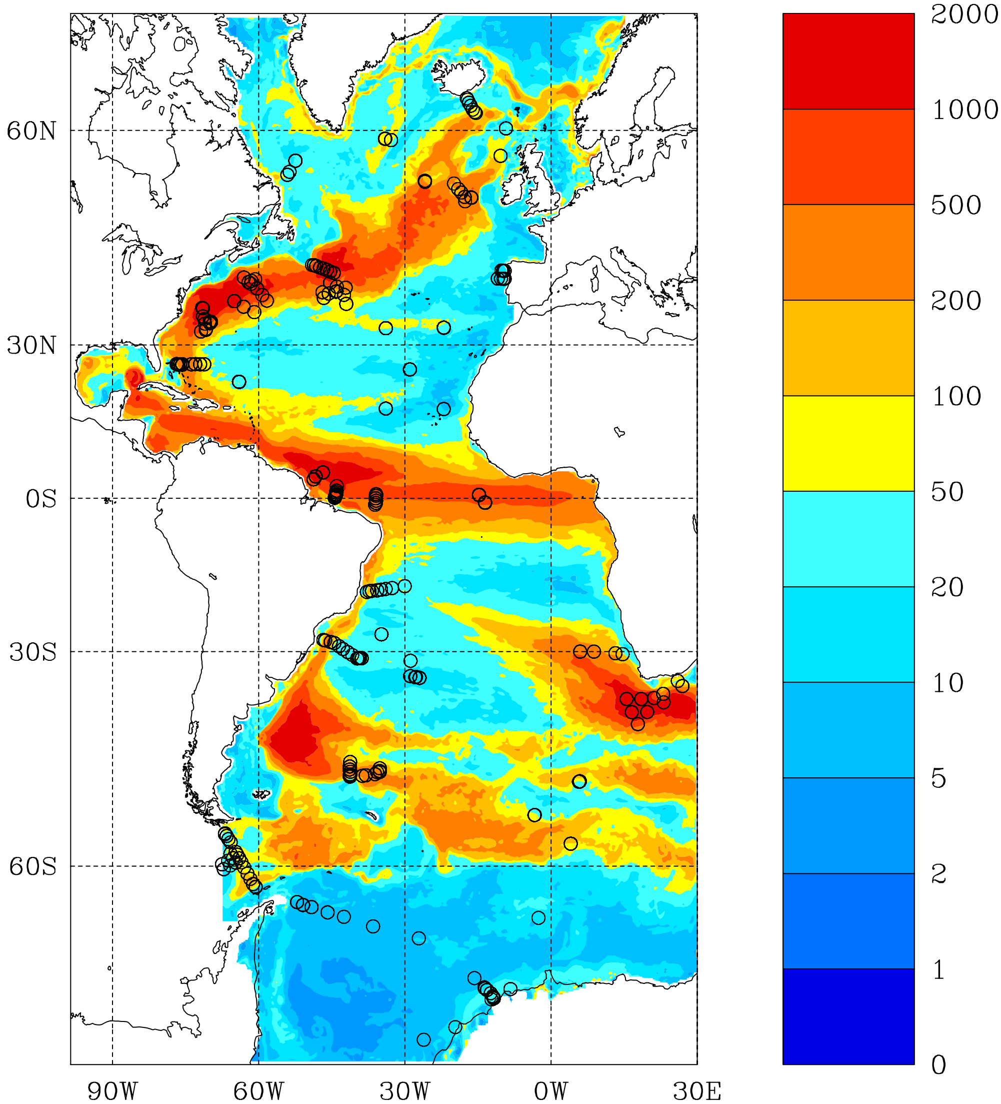

Fig. 10 Surface distribution of eddy kinetic energy (EKE, or intensity of the mesoscale variability) from a 1/6^o CLIPPER simulation of the Atlantic Ocean during the period 1980–2000. EKE is well known globally at the surface from satellite altimeter data. The current meter data collected during the WOCE experiment (moorings locations marked with *black circles*) are used to quantify model–data EKE differences throughout the full ocean depth. This analysis revealed systematic biases of the modeled subsurface circulation

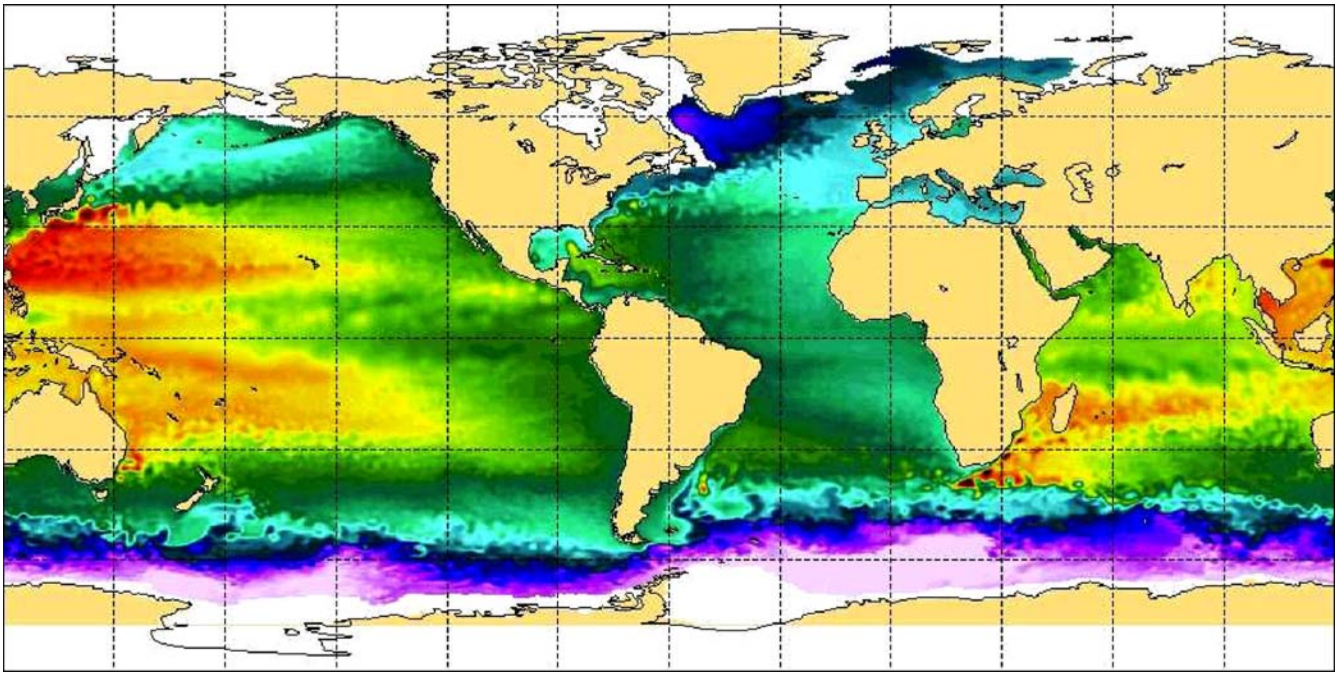

Fig. 11 Instantaneous sea-surface topography and sea-ice cover (*white*) in December from a climatological global DRAKKAR simulation at $1/4^o$ resolution. Such a numerical simulation requires the use of 186 processors of the IDRIS massively parallel computer. The *color scale* corresponds to $+1$ meter for the *deep red* to -1 meter for the *deep blue*; and for south of the Antarctic Circumpolar Current, it reaches -2 meters

interesting stage concerning the model resolution. In the past, increasing the resolution to improve the realism of the ocean circulation was never questioned. Today, the perspective is perhaps changing. During the Drakkar project, we found that an intermediate resolution of $1/4^o$ was sometimes more effective to improve certain parameterizations or certain algorithms than further increasing the resolution. A future challenge is to search for a consistent balance between model resolution, numerics, and the different parameterizations.
- Parameterizations and better understanding of physical processes are more necessary than ever. It is clear that future improvements of global modeling will depend on solutions for internal problems (nonhydrostaticity and subgrid scale processes) but even more critically on solutions for local problems (overflows, surface mixed layer, and interior mixing) and boundary problems (boundary layers, surface forcing, topography and coastlines, ...).
- Lastly, integration remains a key word today. Strengthening the synergy between theory, modeling, observations, and assimilation is the way forward.

3.1 Computing

> *I have had the good fortune to have experienced two major revolutions in my discipline. - firstly, the exponential explosion of computing methods, from which we in France have received the full benefit due to the willingness of our supervisory and their enlightened computer policy* [2]

Over the last 30 years, the computing power available to the French research community has been multiplied by a factor of 10 to the power of 10, from 1 Kflops to some 10 Teraflops today (Fig. 12). At the same time, computing memory has followed roughly the same evolution from 10 Kb to 10 Tb today. Superimposed on these curves are the evolution of the various tidal model developments and the ocean modeling projects. The law of Moore is roughly respected with an increase by a factor of 2.15 in computer speed per year.

It is stimulating to envisage the future prospects for ocean modeling and data assimilation based on an extra-

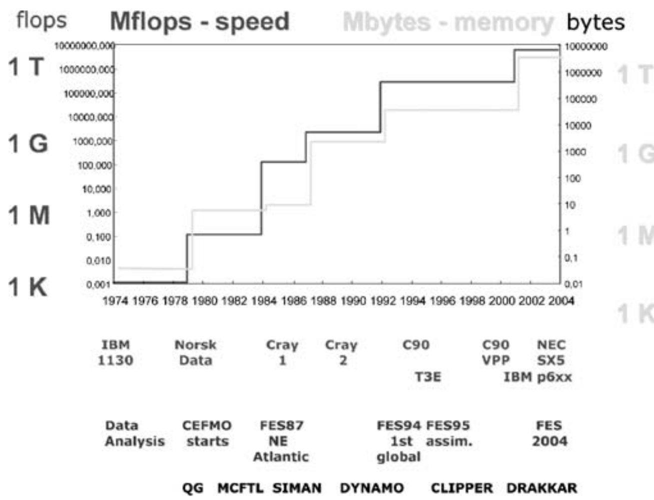

Fig. 12 Computing memory and speed evolutions during the CLP's career. The scale is logarithmic. The time scale also shows the successive computers used by CLP, his tidal models, and the modeling project conducted

polation of the computing power. From today's stage with the 1/4^o global model, we can expect to have a 1/12^o global ocean model running by 2009. In 2007, the global assimilation model using the SEEK filter should be running. And we could expect a 4DVAR version to be running on the 1/12^o global model by 2015.

4 Altimetry

I have had the good fortune to experience the development of satellite observation techniques, and in particular the marvellous adventure of the Topex/Poseidon mission. The harvest to be reaped in terms of the progress resulting from the use of these techniques has only just begun [2]

CLP was involved from the start in the altimetric adventure (Le Provost 1983; Le Provost et al. 1987). We will start by evoking the beginnings of satellite altimetry with Seasat. CLP demonstrated how oceanography could use this type of signal once the satellite orbit is adequately known (Le Provost 1983). In Fig. 13, the right top curves show the signal measured by Seasat for three successive passes of a specific track (left) of the satellite over the English channel. The variations are enormous because the amplitude of the differences from one pass to the other is of the order of 5 m. Based on his physical model of the English channel, CLP computed the contribution of the tides (right middle curves). Once the tidal signal is deducted, we clearly see the coherence acquired by all three signals (right bottom curves). The remaining large-scale differences correspond to orbit errors. The variations around this state of reference are due to the signal which is of interest to oceanographers for measuring currents.

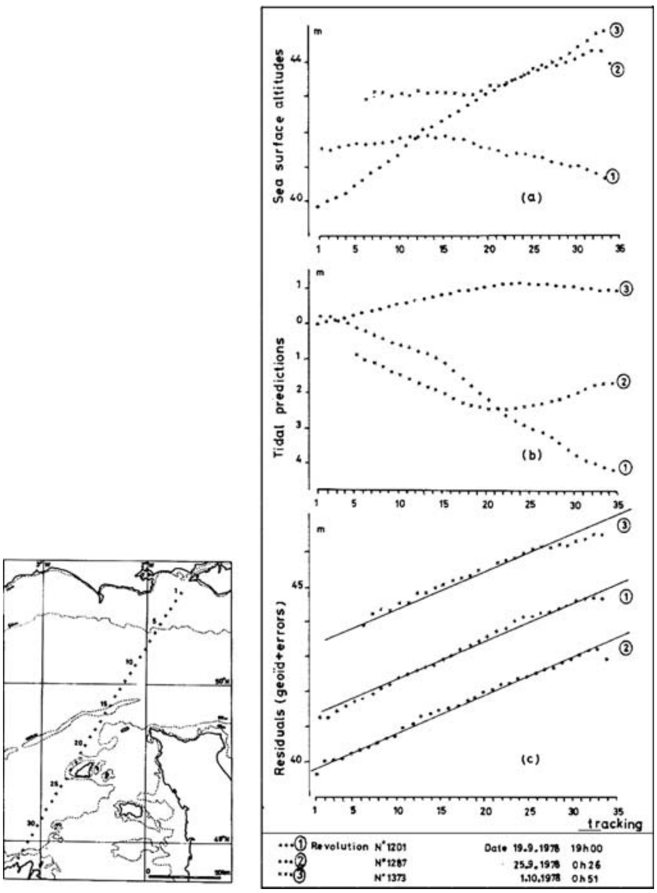

Fig. 13 Seasat altimetry measurements along a track crossing the English channel

Since that period, CLP has been a faithful partner of the altimetric adventure and of the Geosat, Topex–Poseidon, Jason, and Envisat projects (Le Provost 1992; Molines et al. 1994; Le Provost et al. 1995, 1998; Arnault and Le Provost 1997; Le Provost and Brémond 2003; Carrère et al. 2004).

CLP was also involved in building the future of altimetry with the AltiKa project and gravity missions (Visser et al. 2002; Johannessen et al. 2003). Satellites such as AltiKa or WSOA will hopefully precede the future operational altimetric systems using microsatellites. AltiKa is a new satellite altimeter whose concept is based on Ka range measurements. This will allow, among other things, access to the coastal ocean which is not accessible at the moment with standard altimetric measurements. The **challenge** which interested CLP was the possibility of observing the coastal ocean. AltiKa is a minisatellite with a payload much smaller than Topex/Poseidon and Jason. Hopefully, it will be launched in 2009, perhaps in cooperation with India.

In the partnership between altimetry and tides, each partner has truly benefited from the other. Altimetry has revived tidal sciences providing in particular a precise knowledge of the global tidal elevation and currents, a view of the tidal energy budget, and the rediscovery of the internal tides. In the future, it will help in observing and better understanding the shelf and coastal tides, which in turn will help improving coastal tide modeling. There is no doubt that altimetry has opened the route for including tides and tidal mixing in general circulation modeling. High-resolution altimetry is also needed for general coastal ocean applications and in particular for operational oceanography in coastal and shoreline areas.

For the altimetry community, new challenges are currently under investigation, which include more precise shelf and coastal tidal modeling and the interactions between tides and the ocean circulation. Higher resolution altimetry is now needed to go further, especially for coastal applications where the high-frequency dynamics are dominant.

5 Operational oceanography

In addition, the constant progress in the field of numerical computing, in the contribution of satellite techniques and new deep-ocean observation techniques suggests that in a few years we will be able to model the ocean condition in a precise and predictive manner, just as meteorologists are already doing for the atmospnere [2]

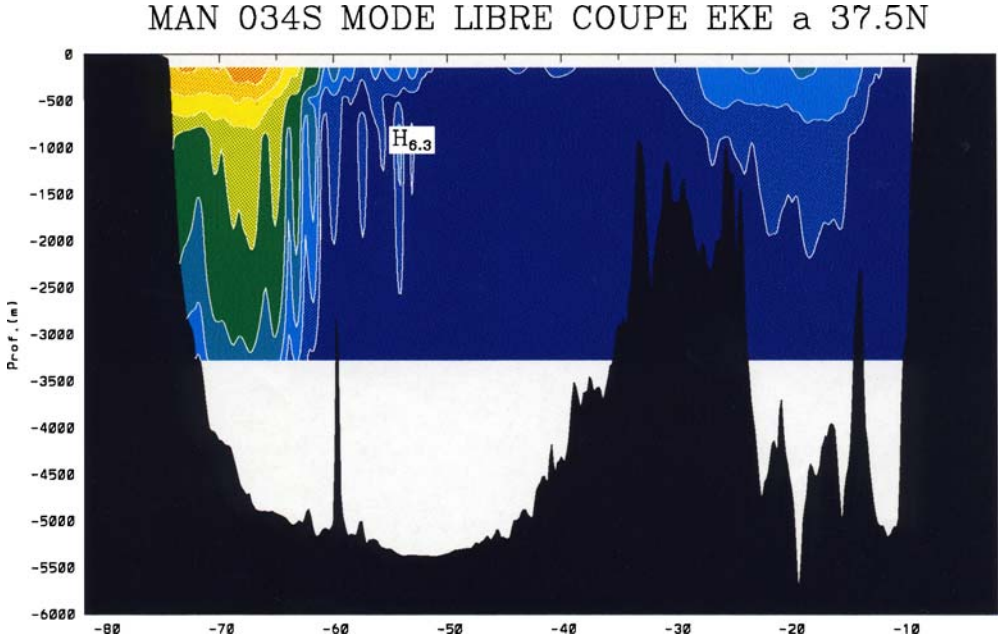

Fig. 14 Eddy kinetic energy vertical section at 375N in the North Atlantic Ocean from the SIMAN "preoperational" project using a four-layered quasigeostrophic model. Geosat data are assimilated into the model with a nudging technique

CLP was strongly involved in the development of operational oceanography. He did everything he could to ensure that there was a transfer of expertise between the fundamental research groups and the operational oceanography centers, which was necessary for the success of projects such as Mercator. Making operational oceanography an integral part of the oceanographic community and using models as an integrating **tool** were certainly the main **ideas** of CLP. Mutual respect between the scientific and the operational oceanography communities was one of the keys and the deep foundations of CLP's **mission**.

The first French prototype (SIMAN-QADRAN) of a preoperational oceanography system with data assimilation was undertaken by the Grenoble–Toulouse groups in the late 1980s (Blayo et al. 1997). It used a simple quasigeostrophic model and had only four layers to represent the vertical dimension. In spite of its simplicity, an acceptable degree of realism was reached, for example with regard to the turbulent energy levels (Fig. 14, Blayo et al. 1997). Even in these early stages, French newspapers were talking of predicting the immediate future of the ocean, as in meteorology, with titles such as: "Quel courant fera-t-il demain? What current will flow tomorrow?".

The truly major founding moment of operational oceanography in France, and maybe beyond, was the meeting convened by M. Lefebvre in 1995 at La Chapelle Aubareil. There, a group of people decided to start the Mercator project (Fig. 15). CLP was there, of course, keeping a father's watchful eye on each. In the municipal news bulletin of the village of La Chapelle Aubareil, this sentence was quoted from the writer and poet, Antoine de St Exupéry, which applies particularly well to operational oceanography:

> "The future is no more than the present to be put in order. You don't need to forecast it, but simply to enable it".

Operational oceanography is worth speaking of, but especially when we recall some of the memorable moments. Once that occurred was during the founding meeting of GODAE, which took place in Fort de France, in Martinique. A short report on the essence of this meeting was provided to the Mercator mailing list. The context is that of the well-known (French) Lucky Luke western comic strip. The four Dalton brothers were there. In addition, CLP as Ma Dalton watched over her boys with her four Colt guns in her belt ...

The operational oceanography idea has grown. The current European program is the MERSEA project, including more than 40 teams from 16 countries. A new dimension is the extension of the concept from physics to ecosystems. CLP was there in Mersea. In particular, it was with his will to promote his ideas on the validation of operational systems and on defining the so-called "metrics".

The remaining **challenges** are to build a European center for operational oceanography that CLP should have liked to be located in France. And the challenge for any

Fig. 15 The group of scientists who decided to launch the Mercator project during a workshop in La Chapelle Aubareil in 1995

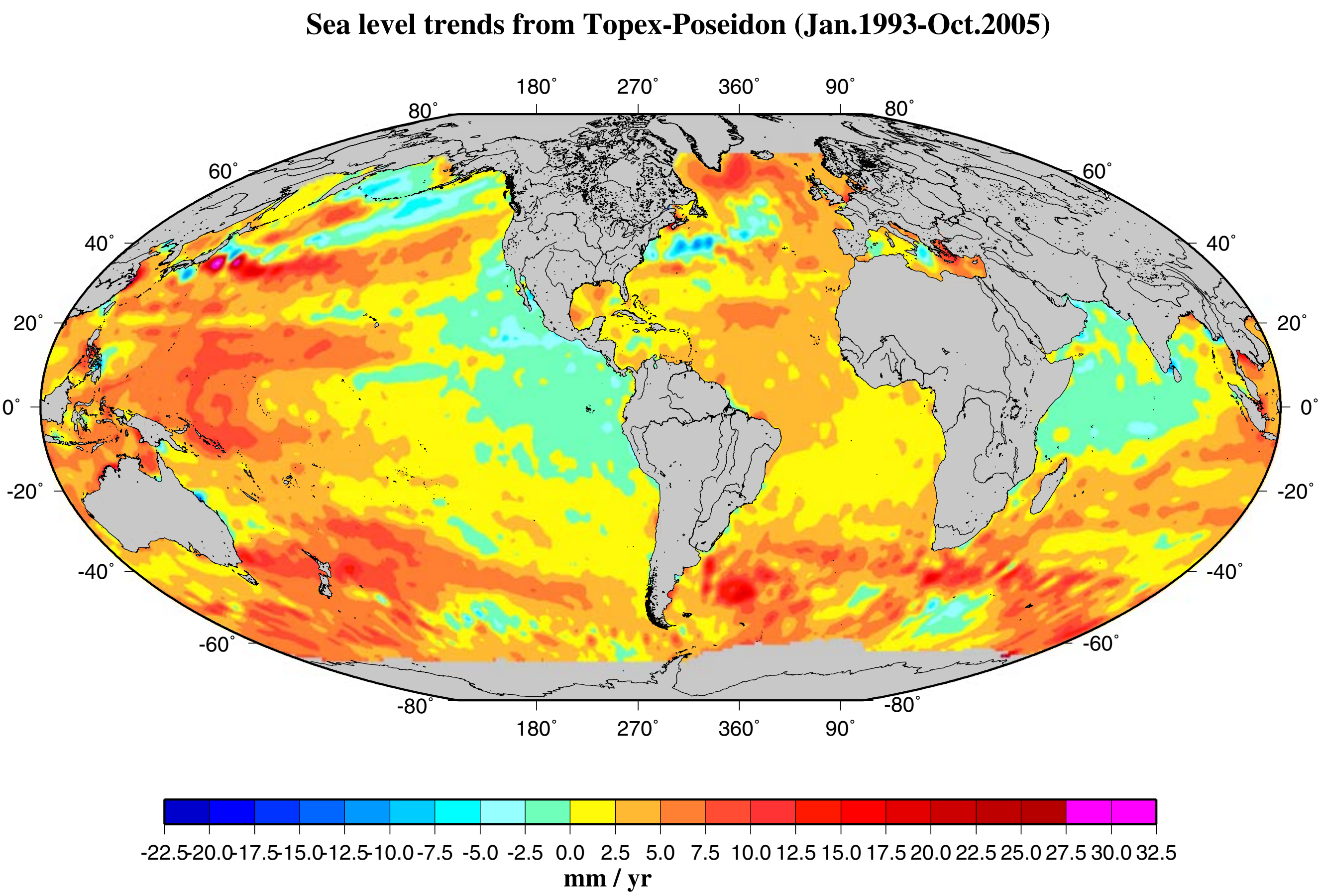

Fig. 16 Sea-level trend as measured from Topex/Poseidon, Janurary 1993 to September 2004

successful operational oceanography center is to keep the strong links with research alive.

6 Sea level

Mean sea-level rise was another centimetric challenge for CLP (Le Provost 1990–1992; Cazenave et al. 1999). Topex/Poseidon and Jason-1 observe a rise of the global

> *Lastly, by collaborating at the international level on continuous in situ sea level observations, and jointly exploiting the satellite altimetric measurements, in ten years from now we should be able to calculate any acceleration in rising sea levels at the planetary scale, and to understand the causes: this is a central theme of the LEGOS* [2]

mean sea level of about 2.6 mm/year. But this rise is far from being spatially uniform. Looking at Fig. 16, one observes that the sea level is rising in the red areas and actually decreasing in the blue areas. The scientific question is why? Is the steric effect the main reason for the sea-level rise?

CLP was interested in extending the world network of tide gauges into zones still free of measurements such as Kerguelen, Crozet, Amsterdam, and Terre Adélie (Fig. 17). Since his early research projects (Kravtchenko and Le Provost 1970), he was committed to improving the observational network and the analysis of existing observations (Ponchaut et al. 2001; Woodworth et al. 2002).

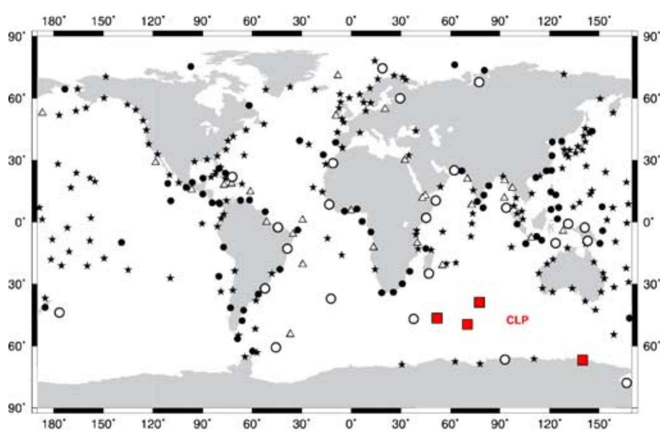

Fig. 17 The GLOSS tide gauge network showing the gauges installed at the initiative of CLP for completing the global network

Perhaps, it was not only a scientific challenge for CLP but a personal one.

It is not an easy task indeed to install a tidal gauge (Fig. 18) near the Kerguelen Islands with the R/V Marion Dufresne. However, using the global tide gauge network to examine the assumption of a steric effect for sea-level rise is a sound idea. CLP made a significant contribution to this debate which is still ongoing (Cabanes et al. 2001a,b). Our current understanding is that this steric effect is responsible for 50–60% of the global sea-level rise.

> *It is perhaps so that I can feel really worthy of my stripes as an oceanographer that I chose to work in the Southern Ocean, in the Crozet-Kerguelen sector, in the roaring forties and the hurling fifties* [1]

7 Tidal dissipation

> *Already I have the satisfaction of experiencing the culmination of lengthy research conducted by generations of scientists attempting to penetrate the secrets of ocean tides. With satellite altimetry, we can now observe them at the global scale with centimetre precision. However, one question still remains unanswered today: where and how is the tidal energy resulting from the coupling of the earth-moon-sun system dissipated ?* [2]

Fig. 18 Tide gauge installed at Kerguelen Islands

There are indeed a lot of major questions related to this issue that CLP raised. The overall question concerns the closing of the energy budget in the ocean and the contribution of tides to this budget (Dehant et al. 1997; Le Provost and Lyard 1997). It is thought that perhaps 1 TW, or about 30% of the total tidal energy dissipation, could occur in the deep ocean through internal mixing, and the rest of the tidal energy (2 TW) could be dissipated by bottom friction. If so much energy involves internal tidal mixing, it is likely that tides play a major role in ocean general circulation and therefore in the ocean climate. A more geodetic issue concerns the energy of the earth–moon system and how tidal dissipation is linked to the earth–moon distance variation and to the variation in the earth's rotation.

Tidal dissipation through bottom friction occurs in the shallow areas of the ocean, particularly on the continental shelves. Remember that these are also the areas where the tidal models have the largest errors. Dissipation through internal waves occurs in the interior of the ocean. Only the combination of global tidal models and altimetry allows us to build such maps.

One important application of all of these concerns the possible energy sources needed to maintain the ocean conveyor belt for the thermohaline circulation. It is thought that 2 TW is required to maintain the great conveyor belt system. The external forcings provide 1 TW, and there has been speculation that the tides, by pumping energy into vertical motions, supply the remainder. So far, the present generation of ocean circulation models ignores the tides. Following CLP's idea, a global model has been tested with a tidal mixing parameter introduced into the ocean interior. The results are rather spectacular (Fig. 19). Oceanographers who look at the meridional overturning cell will understand its implications for the ocean's overall thermohaline circulation. Replacing the internal ocean mixing by tidal mixing does not modify the intensity of the overturning cell at the surface: the North Atlantic Deep Water (NADW) remains roughly at the level of 14 Sv (1 Sv is a million cubic meters per second), but the lower branch

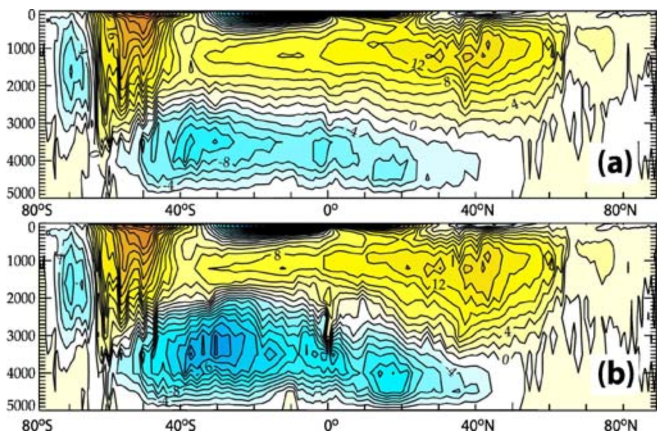

Fig. 19 Global annual mean effective meridional stream function after 1,500 years obtained with ORCA2 for **a** a constant 0.1 cm^2/s vertical eddy diffusivity coefficient and **b** a tide-dependent coefficient. Note the increase of the Antarctic Bottom Water cell and the deepening of the lower branch of the North Atlantic Deep Water cell

of the NADW is deepened. More importantly, the Antarctic Bottom Waters have a deep circulation which has doubled from 10 to 20 Sv and which is quite close to the most recent observational estimates. Tides could therefore be a major ingredient to be accounted for in ocean climate modeling.

For me, this is the last great challenge. I shall be retiring in 5 years time which does not leave me long to explore this question, a question that I honestly thought was beyond the reach of modelling studies, even at basin scale, before our discoveries based on the Topex/Poseidon data [2]

8 Today and tomorrow

The passion of our work has obviously made me forget the passage of time [1]

Christian left us unexpectedly on 29th of February 2004. With him also went his extraordinary passion for his work which he succeeded in passing on to so many of us. Among his qualities, his ability to lead and supervise students and scientists stood out. He was a great human being as well as a great scientist. We are all proud to have worked with him, just as we are proud to pursue his many interests in the coming years.

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