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Ocean Observations and the Climate Forecast Problem

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The widely disseminated and accepted view of the ocean as a nearly-steady, nearly-laminar system is primarily a consequence of the great difficulty of observing it, and of the intense computational cost of modelling it. Uncritical use of the steady/laminar framework has led to a gross distortion of the science, particularly the study of climate change, partly manifested by the belief that a comparatively small number of simple observations suffices to describe the system, and by the inference that oceanic behavior under changed external forcing can be deduced by pure thought without integration of the equations of motion. All of the evidence of the last 25 years shows that the behavior is much more interesting and complex than this distorted view would imply.

Real progress will involve confronting the actual system, not the fictitious one.

A. INTRODUCTION

The problems of observing the ocean have come in recent years to loom large, often because of the importance of the ocean in climate and climate change. Many of the problems are technical ones, but a number of them might be regarded as being more a matter of culture, or of misapprehension, than of science. Whatever the cause, there are consequences for international scientific planning directed at understanding the climate system. Many in the highly sophisticated meteorological community continue to have an antiquated and misleading perception of the ocean circulation, a perception that has led to some surprising assertions about the ocean.

The need for observations of the atmosphere so as to understand and forecast it is a truism of meteorology that few would be inclined to question. One might think that a similar expression concerning the need for oceanic observations would be equally widespread. Experience suggests otherwise. I offer the following quotations, all said in my presence at international meetings:*

1. "The ocean has no physics, and so there is no need for observations. Oceanographers should be forced to stay home and run models" (statement in a climate meeting by a prominent meteorologist—and repeated 13 years later).
2. "The ocean's role in climate change is very simple to determine. One just needs a few high latitude XBT measurements to determine the state of the upper branch of the 'conveyor belt' and everything else can be calculated" (assertion by a different prominent meteorologist).
3. "Observations of the deep ocean aren't necessary. The flow is what Henry Stommel told us it was, in 1958" (assertion by yet another prominent meteorologist).

Such views are hardly universally held. But given that three experienced and influential atmospheric scientists could make these statements in planning meetings is interesting, and worthy of exploration. This exploration becomes a vehicle for a brief survey of where modern physical oceanography has taken the subject, an evolution that clearly has not yet become widely appreciated. That there can be such a wide gap between perception and reality is a consequence largely of oceanographic history, and the junior partnership role physical oceanography has had until relatively recently, relative to meteorology.

B. SOME HISTORY: OBSERVATIONAL AND THEORETICAL

The opacity of the ocean to electromagnetic radiation has meant that for most of the history of the

* Names withheld to protect the innocent (note that the word "innocent" has two distinct meanings). At the RMS Millennial Meeting, prizes were offered to anyone able to guess one or more of the authors of these statements. There were no takers.

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subject, all observations of the ocean were made by sending a ship to some specific location, and physically lowering an instrument to the depth where a measurement was desired. In the era before modern (solid-state) electronics, that is before about 1965, the only measurements that could be made this way were based almost entirely upon mechanical systems. Obtaining useful measurements of a fluid system at high pressures (10 m of water is approximately one atmosphere, and the ocean reaches to depths exceeding 6000 m in many places) without the use of electromagnetic sensors or information delivery devices is a considerable intellectual challenge! A number of extremely clever individuals solved this problem for temperature, salinity, and a few other chemical properties (e.g., crude, by modern standards, oxygen concentration measurements were possible in the 1920s). By the end of the nineteenth century, electrical (rather than electronic) signals from current meters could be sent up cables from ships. Some of the intriguing devices that were developed over the years are discussed e.g., by von Arx (1962).

Consider that oceanographic ships are very expensive devices; today (year 2000), a deep-sea-capable vessel costs about US\$25,000/day to operate (apart from the science costs). Similar great expense was incurred, in suitably deflated monetary units, throughout the history of the subject. (Its beginnings are often traced to the despatch of the Challenger Expedition by the Admiralty in 1873. Even then, it required a military agency to meet the bills.) Such ships remain quite slow, with a modern oceanographic vessel steaming at about 12 knots. At that rate, and stopping periodically to lower devices into the sea, it takes approximately 1 month to work one's way across the North Atlantic Ocean, and about 2 months to do the same in the Pacific Ocean (few oceanographic ships today have the range to do scientific work while crossing the Pacific Ocean). Consequently, no one could afford to have a ship linger very long at any one place, with the limits typically being a few hours to a day or two. Thus *time series* of oceanic variables were almost nonexistent.

To obtain some understanding of the large-scale oceanic fluid structure, oceanographers resorted to combining observations of the ocean from time intervals spanning many decades. Such a strategy can have various outcomes. At one extreme, it fails altogether, with data from one expedition being clearly incompatible with that from another. Indeed, velocity measurements from ships were impossible to use: the flow field was clearly extremely variable in both space and time, changing completely over a few hours and a few kilometres. The other extreme outcome is that the observations are very similar, permitting contouring of large-scale property fields over the entire ocean (an example is shown in Fig. 1) or even the globe. Fortunately for oceanographers, and in great contrast to the velocity field, scalar properties such as temperature, salinity, oxygen (and subsequently a whole suite of scalar properties such as silica, phosphate, and even quasi-geostrophic potential vorticity) proved to be apparently stable, decade after decade, and so, interpretable.

The picture which thus emerged early on in the subject was that of an ocean in an essentially laminar state, unchanging in time, and leading to the "ocean circulation" pictures now available in countless textbooks, both meteorological and oceanographic. In particular, the large-scale thermal and salinity fields permitted gradient calculations to be made over large distances, and the geostrophic (thermal) wind computed. Because of the perceived need to assume a so-called level of no motion to set the absolute value of the thermal wind with depth, in many such flow schemes, this level could be adjusted to produce flow fields supposedly consistent with the large-scale property gradients (see e.g., Reid, 1986) which were then presumed to be representative of the direction and magnitude of the flows.

Somewhat surprisingly, there was essentially no theory of the ocean circulation until the late 1940s (the nearly singular exception being Ekman, 1905). But beginning with the now-famous papers of Sverdrup (1947), Stommel (1948) and Munk (1950), a theory of the wind-driven circulation developed over the next decades (the almost complete failure until the 1980s of the theoretical community to consider the role of buoyancy forcing of the ocean is another remarkable phenomenon). The first models were wholly analytical, steady and laminar. The earliest computers (whose use began in the 1950s) were so small and slow, that the numerical models were also steady and laminar. By the late 1960s, theoretical and observational oceanographers had produced a quite pleasing combination of apparently consistent theory and observation in which the ocean circulation was large-scale, only slowly changing if at all, and apparently describable at least in gross outline by a slow, sticky, quasi-geostrophic theory.

C. THE PERCEPTION

Let us return now and examine the three above quotations in the light of this history, as it will be seen that they make a certain amount of sense in that context. Quotation (1) employs the word "physics" in its strange meteorological usage meaning that the ocean has only "dynamics" and apparently none of the "right-hand

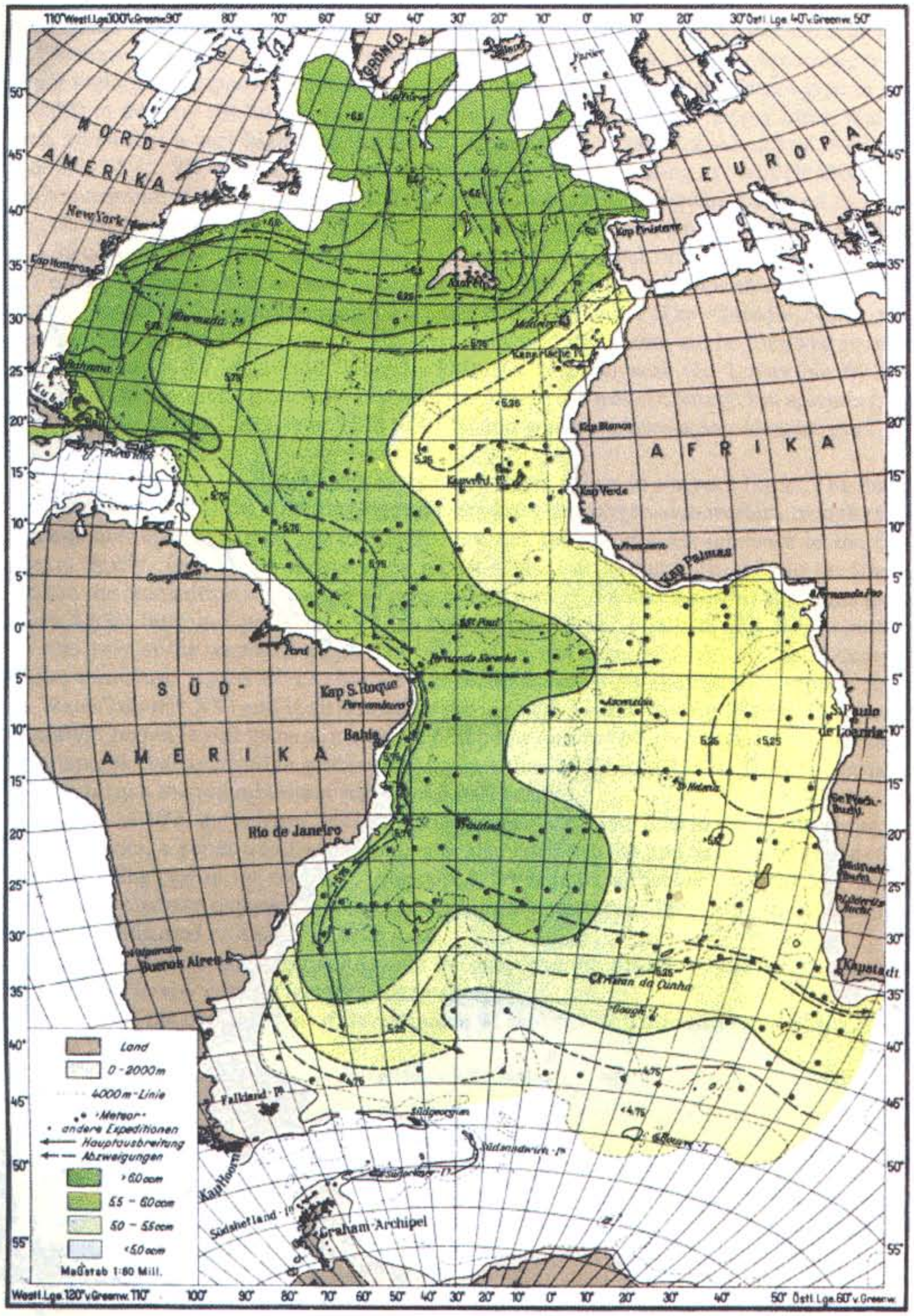

FIGURE 1 A famous picture of the oxygen concentration in the Atlantic Ocean showing the great "tongue" of excess concentration at approximately 2500 m depth (Wüst, 1935). The presence of this, and other such large-scale features, led to the interpretation of the flow as being large-scale (on the scale of the feature itself), slow, and steady.

side" of the meteorological equations. The latter consists of radiative processes, cloud physics, etc. But this assertion, even if one accepts the premise, makes absolutely no sense. The history of fluid dynamics is one of constant interplay of theory and observation (experiment). Pure thought, unattenuated by tests against observation, seems often to lead one seriously astray. Casual perusal of the *Journal of Fluid Dynamics* and similar publications shows how tightly bound the experimental side is with the theoretical, even in the absence of the meteorologist's "physics". Of course, this ignorant comment also fails to recognize how much in ocean general circulation models represents necessary parameterizations of unresolved processes (mixing of several kinds, topography, eddy fluxes, boundary layers, etc.). The mind boggles at the speaker's thought process.

Quotation (2) has perhaps a bit more justification. W. Broecker (1991) created the notion of a "global conveyor belt" which represents the extreme end-view of the ocean as simple, laminar, and steady. Indeed it is a geologist's view of a simple slab-like flow field which is easy to understand and describe. (I decline to reproduce this picture, which most readers will have seen anyway, for fear of reinforcing a misconception that will likely require a generation to pass before it is expunged from the collective subconscious.) Many physical oceanographers, who should know better, have adopted this terminology and picture for their own ends* and thus the wider community has assumed that it must be an accurate depiction of the ocean circulation (in that wider community I include not only meteorologists, but also biological and chemical oceanographers, who may perhaps be forgiven). What is right about the global conveyor belt and what is wrong? Without going into detail, I would make three lists (Box 1).

Below, I will justify some of the statements about the conceptual difficulties, but full discussion of the lists in Box 1 would require more space than is available. For the moment, I will say only that in general, the

BOX 1
THE "GLOBAL CONVEYOR"

Accurate Elements

There *is* a net meridional overturning mass and property transport (although the two are not the same).

Water *does* sink at high latitudes in the North Atlantic Ocean.

The resulting bottom water *does* return eventually to the seasurface in a closed system.

Difficulties. Missing

Water also sinks at high southern latitudes, in amounts roughly equal to that in the North Atlantic.

Water sinks to intermediate depths in many places including the North and South Pacific Oceans.

Much of the water which sinks at high latitudes in the North Atlantic is recycled back to the surface in the Southern Ocean before proceeding.

The bulk of the surface flow of water in the ocean is in the Antarctic Circumpolar Current (about 130 $\times 10^9$ kg s^{-1}), the largest current on earth.

Much of the surface water entering the South Atlantic comes from the Circumpolar Current.

The North Pacific Ocean is a region of apparently minimal upwelling mass transport.

The fluid passing westward through the Indonesian passages appears to recirculate, primarily, around Australia.

The time average circulation is in large part dominated by narrow, strong boundary currents (Gulf Stream, Kuroshio, Agulhas) and in the southern ocean, the heat flux is dominated by eddy processes.

The kinetic energy of the ocean circulation is dominated (two or more orders of magnitude) by the time-varying component (Fig. 2).

Difficulties. Conceptual

The mean circulation is an integral over many small scale, extremely energetic, space and time-varying components.

A change in the high-latitude sinking rate need not translate into a simple shift in a global laminar flux rate.

Stoppage of convection in the North Atlantic does not necessarily mean that it cannot shift to some other ocean.

* The conveyor belt picture *is* a wonderful cocktail party metaphor for nonscientists.

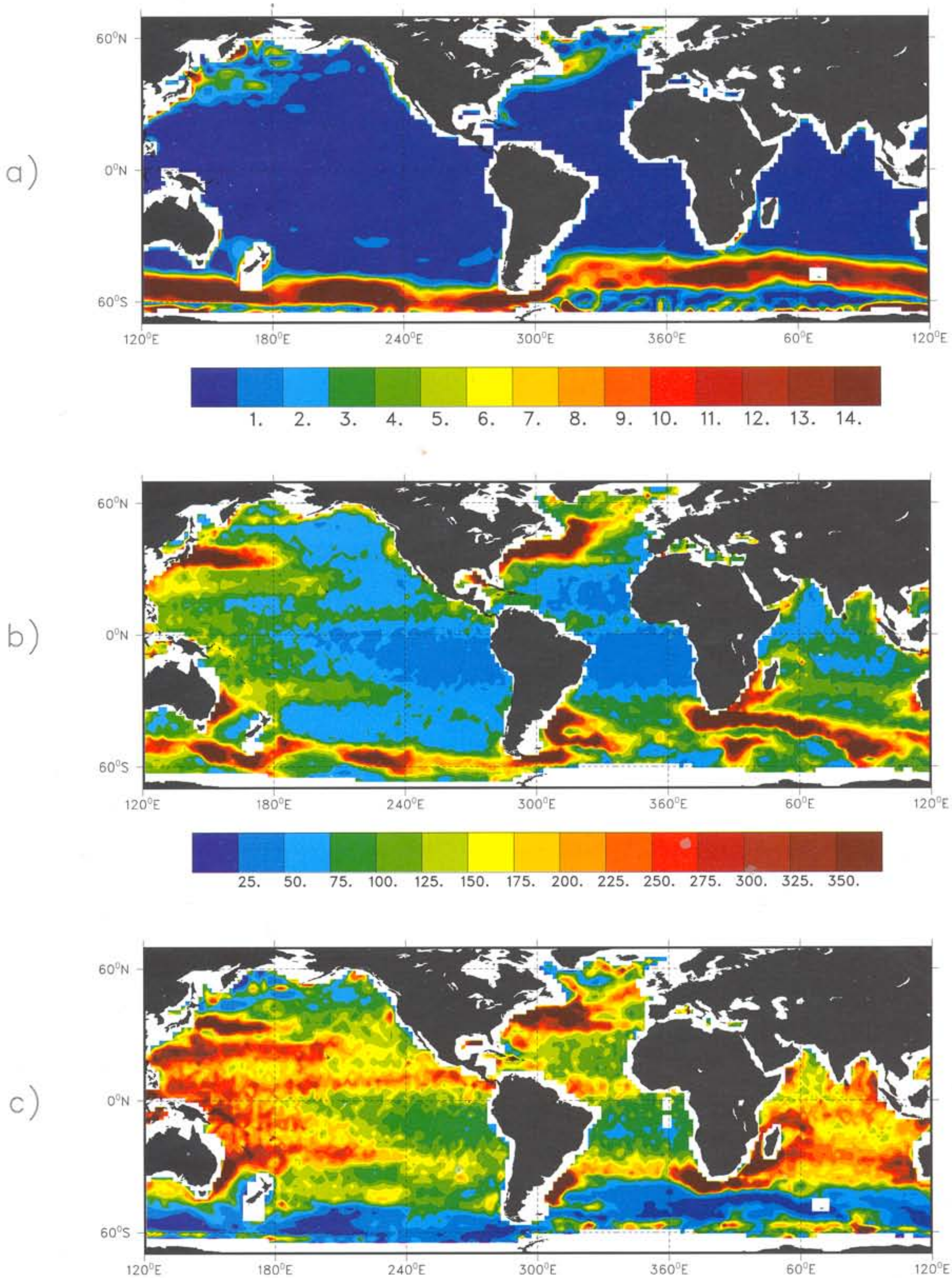

FIGURE 2 (a) The estimated kinetic energy of the seven-year time average ocean circulation as computed geostrophically from the absolute seasurface elevation of the TOPEX/POSEIDON altimetric satellite, and multiplied by f^2 to eliminate the equatorial singularity. (b) Same as the top panel except for the variability about the time mean. (c) The ratio of the kinetic energy of the variability to that of the mean, showing that almost everywhere, the variability dominates the mean. There are bias errors present, particularly in the calculation of the mean flow, arising from spatial smoothing and geoid errors; nonetheless, the figure is at least semi-quantitatively accurate.

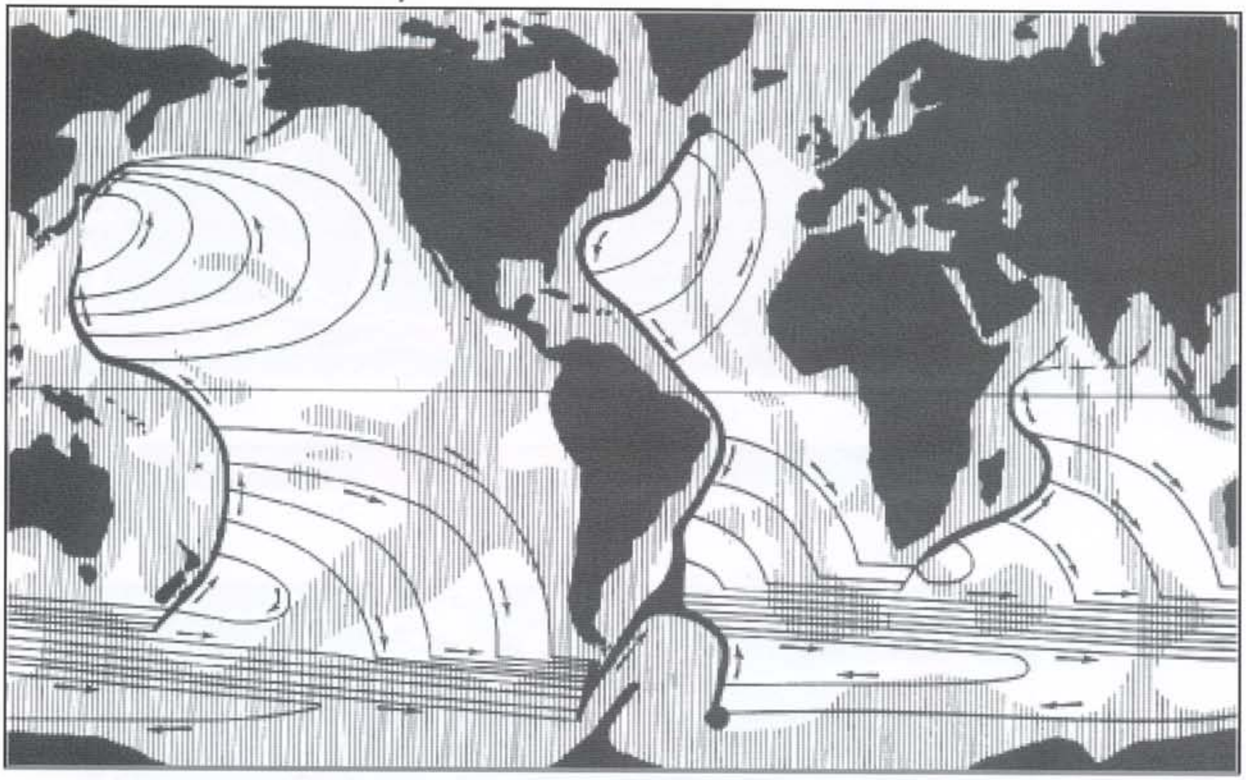

FIGURE 3 The compelling abyssal circulation scheme created by Stommel and Arons in the 1950s (Stommel, 1958). Unfortunately, there is no observational support for the interior flow depicted. What evidence does exist suggests that the interior flows are primarily zonal, with meridional transports taking place in association with intense boundary mixing.

reduction of the complex, heterogeneous, turbulent, time-varying general circulation of a rotating, stratified fluid in a complicated geometry to something diagnosable by pure thought is a remarkable achievement in fluid dynamics—if it is true that it has been done.

Quotation (3) is based upon a famous picture shown in Fig. 3. The abyssal circulation scheme created by Stommel and Arons in the 1950s, another quite compelling, basically simple idea (Stommel, 1948) in what was an intellectual tour-de-force: he recognized that the geostrophic vorticity equation required fluid in the oceanic interior emanating from high-latitude sinking regions, to flow poleward, and thus toward the fluid source. Everything else followed from the requirement of mass and vorticity balance overall, achieved through the presence of boundary currents on the western edges of the ocean. What is usually called the "Stommel–Arons" theory is a beautiful and satisfying construct, and it is commonly asserted (as speaker (3) did) to *be* the deep ocean circulation. Observational evidence for the existence of deep western boundary currents is quite compelling. Unfortunately for this beautiful theory, there is not a shred of observational evidence for the interior circulation scheme that results, and the continued *assumption* that it describes the abyssal ocean circulation has become a major obstacle to progress.

D. THE REALITY

Beginning in the early 1970s, modern electronics had evolved to the point that vacuum tubes were no longer necessary, and pressure cases, and tape-recording technology had improved to the point that one could (nearly) routinely obtain *time series* of oceanographic data. Over the past 30 years, it has become possible to obtain multiyear observations of the velocity field from both moored and freely drifting instruments at great depth. A very large literature has developed on this subject (e.g., Robinson, 1983). What was reasonably evident by about 1975 from records such as the one shown in Fig. 4 that the ocean is intrinsically turbulent. A classical example is the 11-year-long current meter record described by Müller and Siedler (1992) which failed to produce a statistically significant non-zero time

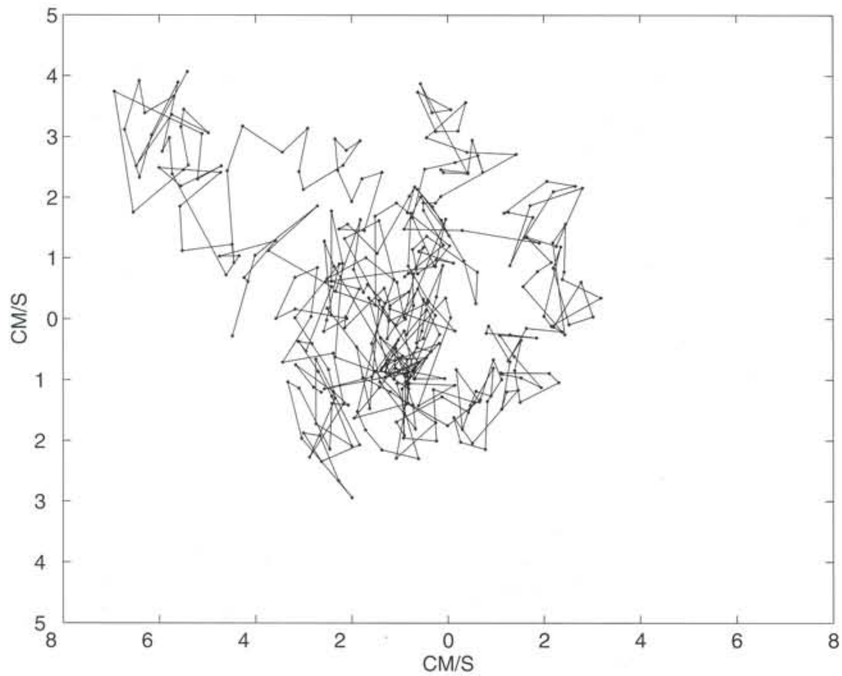

FIGURE 4 Current meter hodograph from 24 h average velocities over 1 year. The record was obtained at 1528 m depth at a position 27.3°N, 40.8°W in the North Atlantic as part of the Polymode program. The result is typical of open ocean records (although this one is quiet). This particular record does produce a mean displacement toward the northwest. If the high frequency components (periods shorter than 1 day) are included (not shown), the figure is an extremely dense cloud.

average of the highly variable velocity measured at depth in the eastern North Atlantic. (Early physical oceanographers (e.g., Maury, 1855; Helland-Hansen and Nansen, 1920) had clearly been aware of the presence of time-varying elements in the ocean circulation; little could be done to understand them, and ultimately the collective subconscious tended to treat them simply as a "noise".)

With the acquisition over a generation of a slowly growing data base, it has become clear that few if any elements of the ocean circulation are truly steady. The literature of the past 25 years is filled with studies expressing astonishment that new observations suggested that almost everything, when examined in detail, appeared to change and that the circulation of the ocean is not actually steady. One example (Fig. 5) will have to suffice. It shows the movement of neutrally buoyant floats (at a depth of 2500 m) in the Brazil Basin, exactly the region where the great oxygen tongue (Fig. 1) has been used to infer a laminar drift toward the south along the western boundary.

Perhaps the single most concrete evidence of the degree of temporal variability in the ocean has come from satellite altimetry (e.g., Fu *et al.*, 1994; Wunsch and Stammer, 1998). In particular, the TOPEX/POSEIDON spacecraft, which was flown by the US and French space agencies in the teeth of fierce arguments from much of the oceanographic community that it would be useless, has demonstrated a truly remarkable degree of variability in the oceans and has been assimilated along with other data into a global general circulation model (Stammer *et al.*, 2000) using the method of Lagrange multipliers (adjoint method). This variability is best appreciated from animations (available from the author), but one static figure will have to do here: Fig. 6 shows the assimilated model surface elevation anomaly at 2-day intervals during January 1994. Each centimetre of elevation difference corresponds to approximately 7×10^9 kg s^{-1} barotropic water transport in 4000 m of water in midlatitudes. These rapid changes are indeed largely barotropic. That the elevation changes significantly over a few days is meant to be apparent (the animations are much more striking).

There is a large-scale oceanic circulation, which appears to be stable over decades, but expected to be slowly changing everywhere in ways we do not understand because we do not have adequate measurements of it. To what extent does this slowly changing part of the circulation dominate the movement of properties in

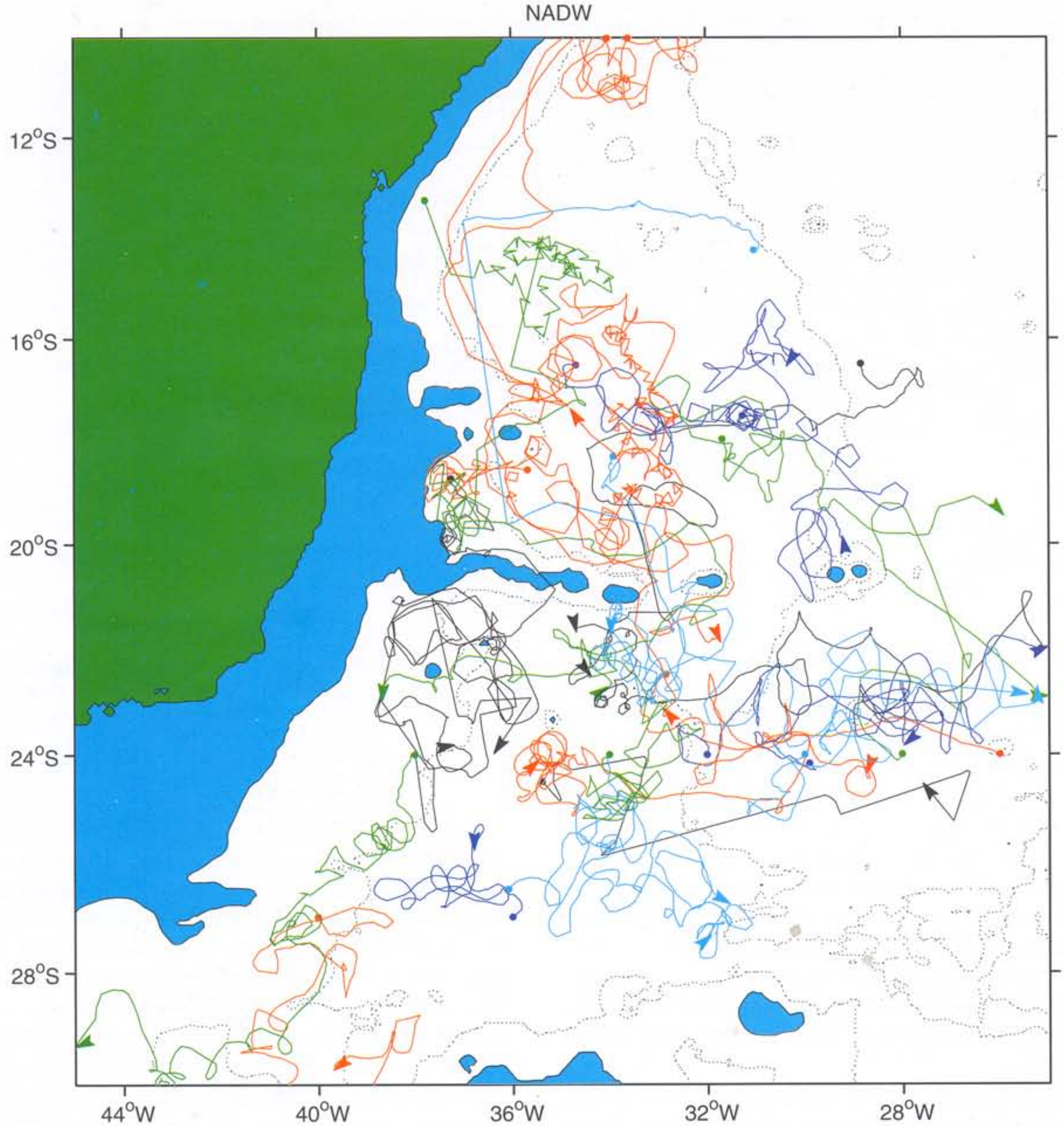

FIGURE 5 Movement over 800 days of neutrally buoyant floats in the region of the great oxygen tongue of Fig. 1—the depth of the North Atlantic Deep Water. This water mass has always been supposed to be moving slowly, more or less uniformly, southward, but the floats show that the movement is actually more east–west and with an extremely complicated structure (Hogg and Owens, 1999; N. Hogg, personal communication, 2000).

the ocean of importance to climate? This question can only be answered by a quantitative knowledge of the property transports of both the time-varying and quasi-time independent components.

With the benefits of hindsight, one perceives that the large-scale property structures in the ocean (the great "tongues") need not imply any large-scale time-mean flow. Quite turbulent flows are capable of producing large-scale structures in scalar properties, representing integrals over very long times and distances of the fluctuating movement of the circulation. One's eye is captured by the largest scale structures (it is apparently an evolutionary advantage that humans developed the capacity to see subtle large-scale patterns superimposed upon very complex backgrounds). But in most cases, it is the spatial gradients of these structures, not the struc-

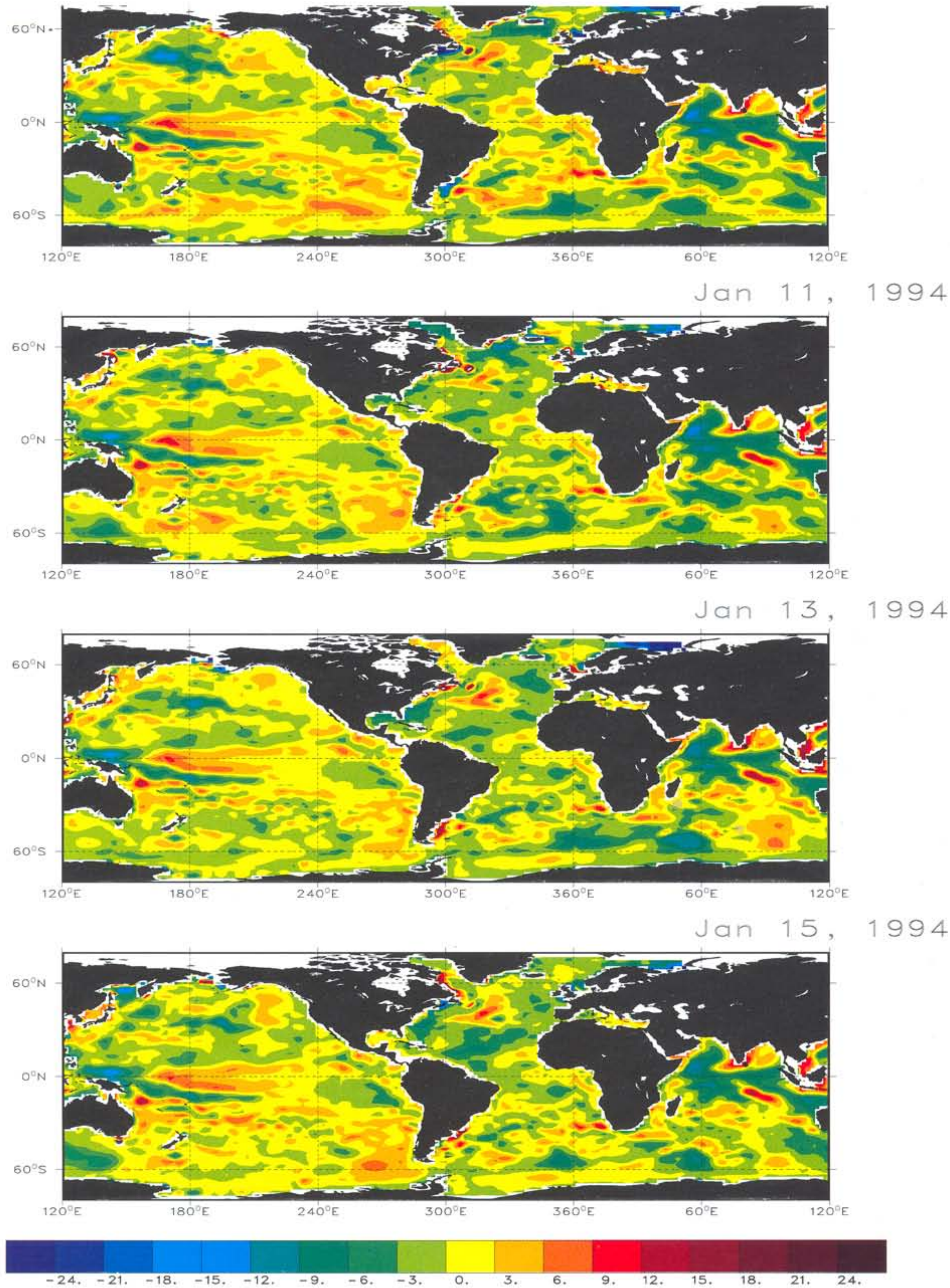

FIGURE 6 Sea surface elevation anomaly (relative to a six-year mean) from a fully assimilated ocean general circulation model. Even at intervals as short as 2 days, there are significant, and dynamically important shifts in the flow field (see Stammer *et al.*, 2001).

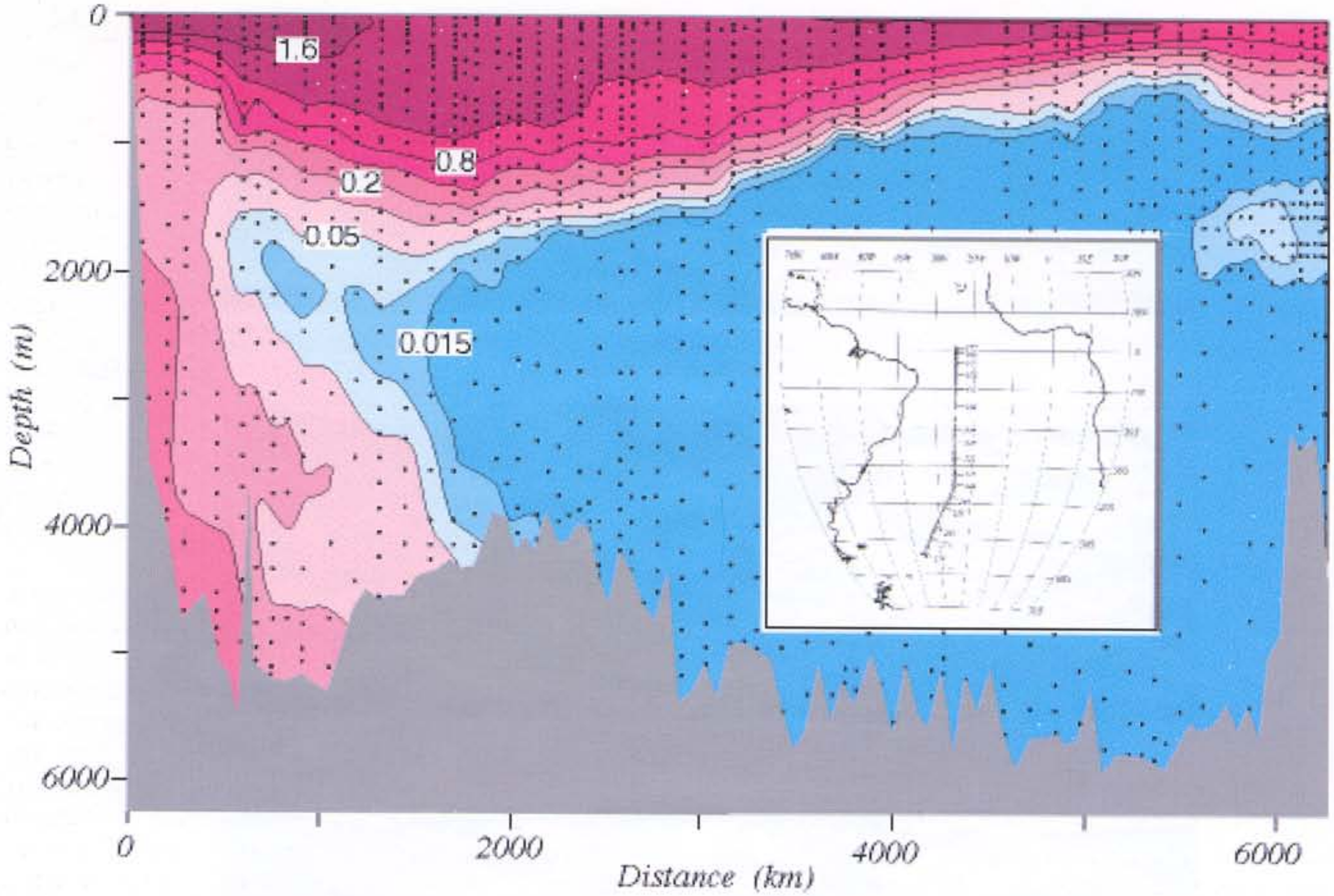

FIGURE 7 Freon, F-11, as observed during 1989 by Weiss *et al.* (1993). Within 30 years of the steep increase in atmospheric concentration, the tracer is found in the abyssal ocean far from its source. Disruption or enhancement of such connections could obviously have serious consequences for climate.

tures themselves, which are of dynamical and kinematical significance, and which are very difficult to estimate by eye. No one, to my knowledge, has attempted to produce global contours of the lateral *gradients* of the large-scale fields.

The history of oceanography is littered with appealing, simplifying, ideas, that had ultimately, to be painfully dislodged. The problem is further compounded by the fact that models have become so sophisticated and interesting, it is tempting to assume they must be skilful. This is a very dangerous belief!

E. CONCLUSIONS BASED UPON MISAPPREHENSIONS

The distorted view of oceanic behaviour based upon the various historical pictures has led to some ultimately crippling misunderstandings about how the ocean operates. For example, it is still common to hear it said that oceanic timescales are so long that it cannot change for hundreds, if not thousands, of years. This statement is commonly coupled with the assertion that one can ignore the ocean abyss for understanding climate change in time periods shorter than hundreds to thousands of years. Yet the fallacy of this view has been in evidence for at least 25 years. As a single example consider Fig. 7 (from Weiss *et al.*, 1993) showing Freon, F-11, as observed along a meridional section in the South Atlantic Ocean. Within 10–20 years of the onset of this transient tracer in the atmosphere, it is found on the floor of the ocean, hundreds of kilometres from the injection point. One might like to assume that these surface/abyssal connections (they occur all over the world ocean) are for some reason, unchangeable. But why should they be unchangeable? If one disrupted this vertical exchange, the near-surface properties could become entirely different very quickly. (The reader is reminded too (see, e.g., Boyle 1990) that the palaeoceanographic evidence is for massive changes in the ocean circulation on timescales hardly exceeding 10 years, a timescale consistent with what is known about the vertical connections such as seen in Fig. 7)

Another, very serious, climate issue arises from the distorted picture of the ocean. If the ocean is a simple laminar system, then very coarse general circulation models can be used to calculate how it will change under changing external conditions, e.g. doubled CO_2. It is not uncommon to see published calculations of future climate states obtained using ocean models with a spatial resolution as coarse as 4° laterally. Although the writers of such papers would undoubtedly deny that they are producing "forecasts", the reader is usually given little or no guidance as to the actual expected skill of such models. Is it plausible that a 4° or even 1° ocean model can be integrated with skill for 1000 years? If there is real skill, then the modelling community has solved one of the most difficult of all problems in turbulence: that of a rotating, stratified fluid in a complex geometry. What is the evidence for its truth?

Some simple "back-of-the-envelope" calculations show the scope of the problem. Consider one example. Much of "climate" is governed by the movement through the ocean of fluid properties (temperature, salt, carbon, etc.). Suppose one's model has a 1 mm s^{-1} *systematic* error in the computed velocity (Lagrangian) of a fluid particle. Then at the end of 100 years, one has a 3000 km position error for that particle. In terms of where enthalpy, carbon, etc. are located in the ocean, and where and how they may re-enter the atmosphere are concerned, errors of this magnitude can completely reverse the sign of the atmosphere–ocean exchange. Do ocean models have errors of this size? I have no idea, as it seems not to have been worthy of study, because "everyone knows" the ocean is laminar and simple. F. Bryan (personal communication, 2000) has shown that the so-called POP-model (Smith *et al.*, 2000) undergoes a sign reversal in the air–sea heat flux in the crucial area of the Grand Banks when the model resolution is shifted from 0.2° laterally to 0.1°. In general, ocean models are not numerically converged, and questions about the meaning of nonnumerically converged models are typically swept aside on the basis that the circulations of the coarse resolution models "look" reasonable.

There are many other examples. I have written elsewhere (Wunsch, 2001) about the conflicting "paradigms" of the ocean circulation and the consequent difficulties in designing proper programs to understand the system.

F. WHERE DO WE GO FROM HERE?

To some degree, everything said above can be reduced to the statement that "absence of evidence was taken as evidence of absence". The great difficulty of observing the ocean meant that when a phenomenon had not been observed, it was assumed to be not present. The more one is able to observe the ocean, the more the complexity and subtlety that appears. To the extent that estimates of the climate state omit physical (and chemical and biological) processes which have either never been observed, or not understood, any forecast, or even statement that "we understand it" will remain vulnerable to suggestions that the omitted processes are (1) present, and (2) represent serious systematic errors which fatally compromise any possibility of a skilful climate forecast.

At its worst, the assumption that the system is much simpler than it actually is, leads to the corruption of an entire literature. Readers of palaeoclimate papers in particular, will notice that extraordinarily complicated and far-reaching changes in the climate system are often reduced to simple assertions about how the "global conveyor" changed. In effect, these authors believe that the equations of motion governing the general circulation of the ocean can be solved and integrated for thousands or millions of years in one's head. One might be suspicious of such claims about the atmospheric circulation. I am unaware of any concrete evidence that modelling the ocean is any simpler than modelling the atmosphere. Indeed, one might readily infer that it is much more difficult: the deformation radius in the ocean is an order of magnitude smaller than in the atmosphere, producing small-scale permanent features capable of transporting properties over large distances (e.g., the boundary jets; see Fig. 8). The ocean has a "memory" in some elements of at least hundreds of years, meaning that long-ago interactions with the atmosphere are still in principle manifest in the ocean we see today.

Oceanography is a branch of fluid dynamics on a grand scale. I believe that the lessons of fluid dynamics tell us that one should remain quite sceptical of any theory or model which has not been carefully compared to observation. There are too many examples, even within oceanography itself, where some important phenomenon, which in principle could have been predicted by theory or model, was not thought of until observations showed its importance (Wunsch, 2001). Examples are temperature and velocity microstructure, the intricate current regime near the equator, the dominance of high-latitude barotropic fluctuations, and the recent realization that the ocean probably mixes

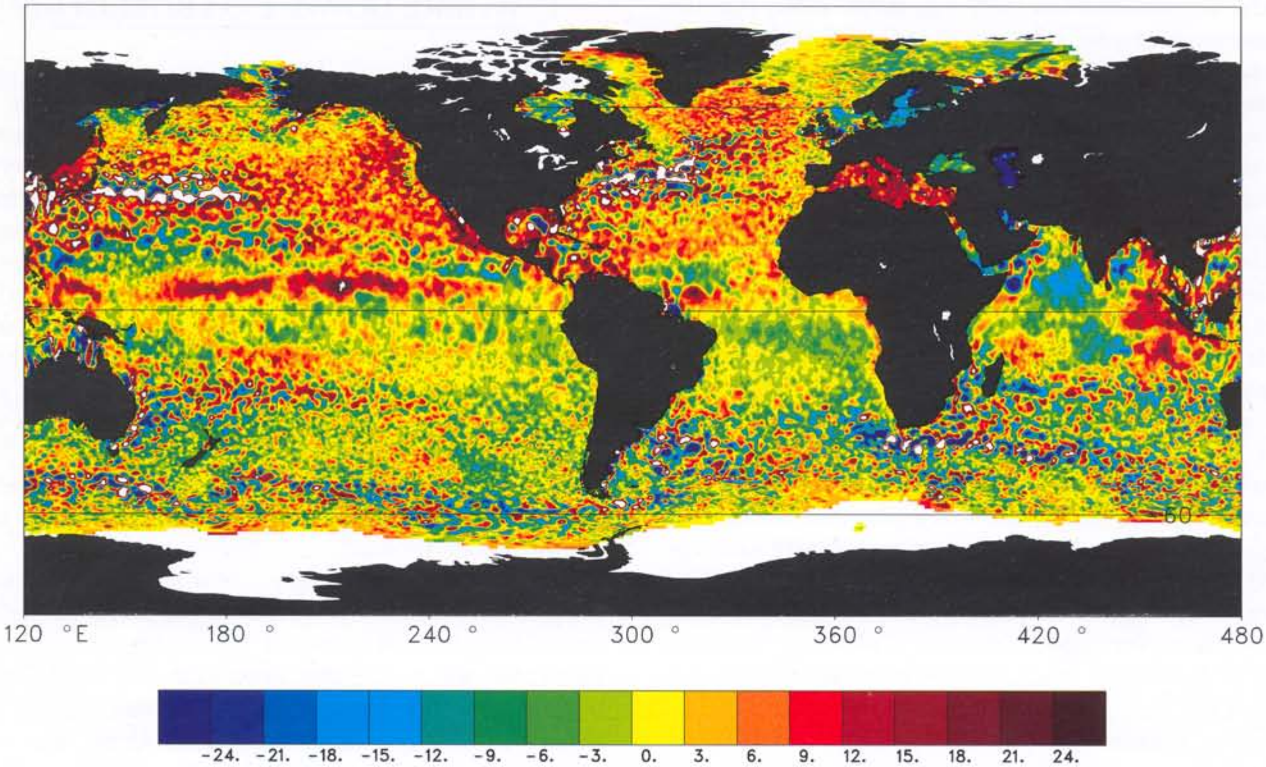

FIGURE 8 Surface elevation anomaly (cm) for the ocean during one 10-day period obtained by combining data from two altimeteric satellite systems (TOPEX/-POSEIDON and ERS-2) and using an objective analysis scheme with a 10-day *e*-folding decorrelation time. The extraordinary fine detail is none the less still a somewhat smoothed version of the true field, owing to the incomplete coverage and blurring by the 10-day interval.

primarily at its boundaries—in flagrant conflict with almost all GCMs.

The moral of the tale is that we need, and will surely continue to need for many years, an adequate set of observations of the ocean. Advancing technology is making the ocean ever-more accessible, although much cleverness will still be required. To a very large degree, however, the problems are less technical today than they are sociological, as alluded to in the Introduction. Oceanographers, in bleak contrast to meteorologists, do not have a customer for sustained observations. Meteorologists are both blessed and cursed by the need to produce weather forecasts. They long-ago convinced governments that for weather forecasting to be feasible, one must have adequate observations and consequently, vast sums are expended each year around the world to sustain *in situ* and satellite measurements of the atmosphere. Nowhere in the world do oceanographers have a governmental commitment to sustained large-scale observation systems. Indeed, the great bulk of large-scale measurements are still made today by individual scientists. Although the satellites have made a large difference to oceanography in the past decade, none of the oceanographic satellites of the most urgent importance (altimeters, scatterometers) is yet regarded as operational. They are thus vulnerable to shifts in government priorities and fashions.

Lest my opening quotations be perceived as unfairly pointing a finger at meteorologists, let me end with another quotation:

> "Programs like WOCE [the World Ocean Circulation Experiment] represent a Fall from Grace. They make oceanography too much like meteorology. Real oceanographers make their own observations."

This comment (in a widely disseminated email message) was made by an oceanographer, albeit a highly theoretical one. If adequate observations are regarded as incurring Original Sin, evidently the cultural shifts necessary to address the ocean fluid problem will not come easily. In the absence of operational government agencies, the oceanographic problem can only be solved with the direct and immediate assistance of the corresponding meteorological-cum-climate agencies. The first order of business is evidently, to be clear that everyone understands the problem, and to recognize the great influence past assumptions exercise over future necessity.

ACKNOWLEDGEMENTS

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