CLIMATE CHANGE AND THE OCEAN OBSERVING SYSTEM

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ABSTRACT *- Long-term changes in our environment and their relationship with the ocean are discussed with a focus on ocean observations needed to detect, understand and simulate this change. Irrespective of the existence of detectable change due to anthropogenic effects, it is argued that ocean observations are needed to equip future generations with the information they will need to address climate issues and to uncertainty about change. The focus on relatively small, long-term changes has direct implications for the ocean observing system including an increased emphasis on homogeneous, global coverage and high quality. Specific objectives relating to climate change issues are discussed. The oceanographic contribution needs to be developed within the context of a comprehensive climate observing system with the aim of establishing long-term, high-quality records. Integration with other elements of the ocean observing system is essential. A selection of the key products is discussed to illustrate where priorities should be directed.*

1 - INTRODUCTION

The climate system is extremely complex and involves interactions among the various components of the biosphere and geosphere at a variety of space and time scales that ultimately determine the environment within which we exist. The most recent meeting of the Joint Scientific Committee for the World Climate Research Program (WCRP 1997) argued that climate should in fact be regarded as the mean of the ensemble of environmental states (the average environment) and thus remove the divide between weather and climate. Using this logic, we should regard climate (environmental) change as a significant departure outside the previously accepted spread of ensemble states, be it due to natural or unnatural perturbations of the states of the geosphere and biosphere. Indeed, with this view of climate change, the distinction normally accorded to so-called anthropogenic change is dulled and the challenge simply becomes one of understanding and predicting environmental change. The Second Assessment of the Intergovernmental Panel on Climate Change (IPCC) did conclude "the balance of evidence suggests that there is a discernible human influence on global climate" (IPCC 1995). However, with respect to the ocean observing system, the attribution of cause is really not an issue. The real challenge is to implement a system that can measure change, no matter its origins, with accuracy and resolution that minimizes ambiguity and uncertainty.

Within this paper we will not address issues of attribution or detection explicitly, nor will we be assessing the scientific evidence for climate change. Rather we will be viewing the worth of the observing system from the perspective of a community concerned with long-term changes in the environment. What do we need to do to ensure the current generation and those that follow are able to grapple with this problem armed with appropriate and representative measures of variability in climate? Will our observing system be capable of distinguishing longer-term trends and/or variations? Will it replace uncertainty with certainty with regards to assessments of change?

There is no dispute within the climate research and applications community that the ocean is an important component. Moreover, it is generally accepted that the large heat capacity and "memory" of the ocean and its circulation are a first-order-controlling factor for long-term change. The ocean is a natural integrator of high frequency and wave number variations and serves to amplify the signal of slow variations relative to more rapid fluctuations in the atmosphere and over land. Moreover, it plays a key role in the carbon cycle through sequestration into the abyssal layers and exchanges at the land and air-sea interfaces. It is logical then, in a Conference on the Ocean Observing System for Climate, that climate change issues be given special emphasis and that appropriate consideration be given to observations that address the needs of the Parties to the UN Framework Convention on Climate Change (UNFCCC).

2 - ISSUES OF CLIMATE CHANGE

A Report on the Adequacy of Global Observing Systems (GCOS 1998) was presented to the fourth Conference of the Parties to the UNFCCC (COP 4) with the focus on observations relevant to climate change. This report highlighted the responsibility of the present generation to arrest the decline in the current observing network and to take measures that would ensure following generations would be able to distinguish change that might have resulted from human activities from changes due to the natural variability of the climate system.

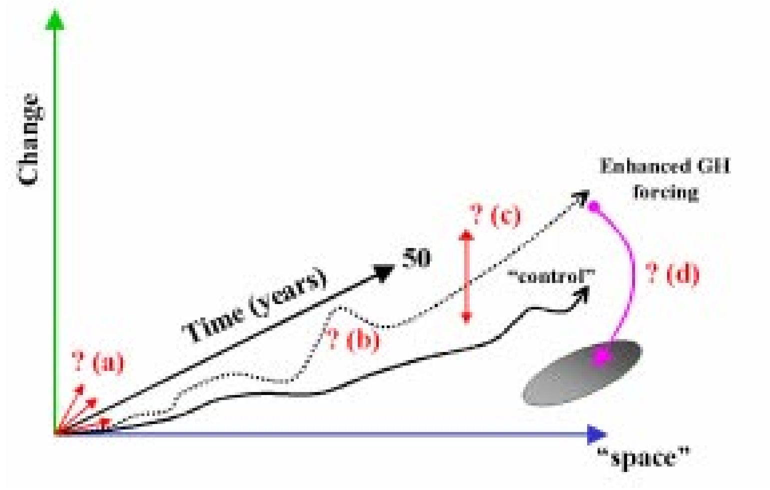

Figure 1. Schematic of sources of uncertainty. (a) The initial condition of the ocean may influence the initial trajectory; (b) Natural variability like the North Atlantic Oscillation might introduce signals much greater than that due to climate change; (c) There is considerable uncertainty due to the unknown rate of enhancement of the greenhouse effect; and (d) There is further uncertainty as inherently large scale signals are projected to regional scales. The ocean contributes to each of these uncertainties.

There is widespread agreement that greenhouse gases are capable of modifying the global radiation balance and that, if the emission of these gases is increased due to human activities, then we might reasonably expect some modification of the global radiation balance. This in turn would lead to changes in the climate system as a whole. Detecting such changes is a formidable challenge, not the least because it must be detected against a background of considerable natural variability. Figure 1 attempts to show schematically some of the sources of uncertainty in "predictions" of future climate. The rate of emission of greenhouse gases clearly provides one of the greatest sources of uncertainty. There is also uncertainty due to imperfect knowledge of the initial state and, perhaps more importantly, to errors in the models (and "natural" model-to-model variations; Fig. 2) used to generate simulations of the future climate state. There is, however, also considerable uncertainty due to the "noise" provided by natural variations in the ocean state, of which, perhaps, El Niño is the most prominent. Such fluctuations introduce added uncertainty to both the forcing scenarios and to the initial state. However, even more importantly, they introduce a level of unpredictability that limits our ability to accurately forecast future climate states. Removing this "noise" from measurements of climate change also represents a considerable challenge.

An immediate conclusion is that we will forever be faced with uncertainty if we do not, first, attempt to quantify this level of natural variability and, second, attempt to understand its role in long-term change. High quality ocean data are mandatory if we are to equip future generations with the information they need to deal with these issues.

It is often assumed that we have adequate observations to monitor climate change. However, if we visual our knowledge in terms of the volume of samples we have taken of the climate system and, more relevant to this discussion, of the ocean over the globe over the last 100 years, quite clearly we have managed only to shed light on a few very select locations. For the ocean, it is arguable whether we have any records that truly qualify as climate reference data sets, sea level and sea surface temperature perhaps coming closest. There are significant regions of the global ocean for which we effectively have no information and the current data base is predominantly from the last decades and focussed in just a few regions like the North Atlantic.

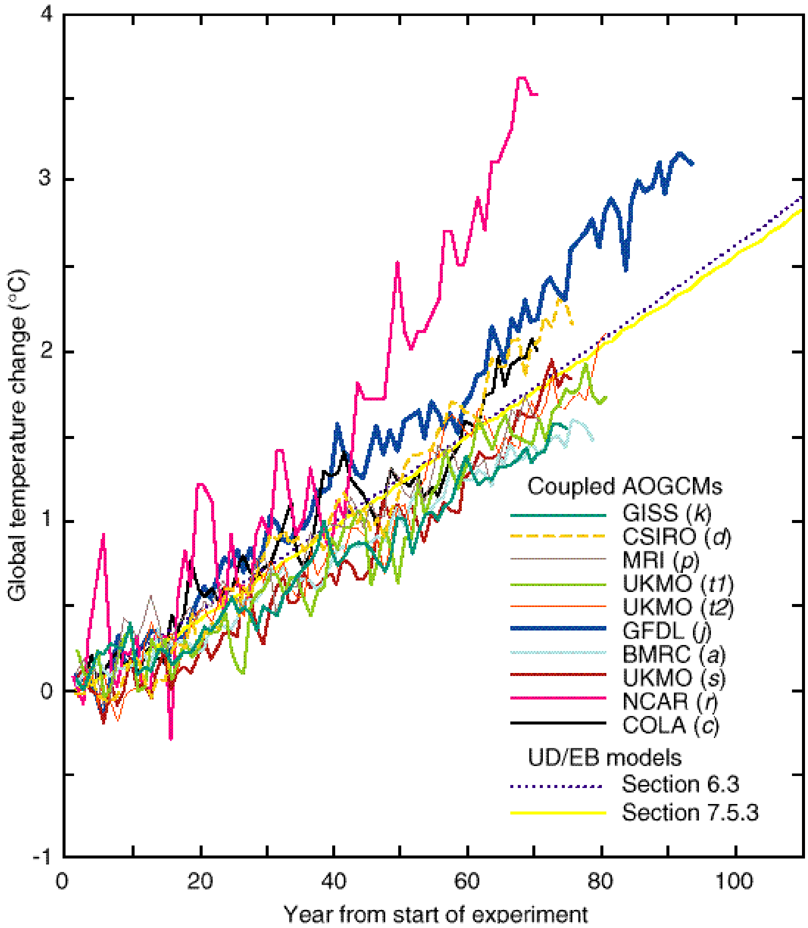

Figure 2. Comparison of several coupled climate models forced with 1% compound increasing concentration of greenhouse gases. The sensitivity of the general circulation models ranges from around 2C to 4.5C at 50 years. Also shown are results from simpler energy balance models. [From IPCC, 1996.] The ramification for the observing system is that the annual changes are small (order 0.1C) so that a very accurate measurement system will be needed to validate these models.

That we have intolerable gaps in the ocean database is without dispute. The next question then is, do we continue to tolerate such gaps or do we focus our effort on those places where records, albeit limited, do exist? The immediate answer is often to focus on those land, air and sea records that are presently judged useful. With the focus on the present, this is undeniably a good strategy. However, if we turn our attention to the future, say 50 years from now, this will be seen as a poor strategy. Those same gaping holes in spatial coverage would remain and the uncertainty attributed would remain high. Certainly the records that were maintained would be longer but this gain would be far outweighed by the uncertainty from spatial inhomogeneity. Far better that these gaps be addressed now, to the extent that resources allow, all the while maintaining those records that are now delivering high quality, long-term records. We are benefiting now from the foresight of generations that have preceded us; the responsibility of this generation is to ensure that future generations will too be appreciative of the thought and planning we put in now.

The thesis of this paper is that the oceans are the best place to start this process. The signal-to-noise ratio is favourable and we have emerging technologies that will allow us to take measurements cost effectively. The challenge is to implement such systems in a way that ensures delicate climate change signals are retrievable with a minimum of ambiguity.

3 - WHY CLIMATE CHANGE NEEDS AN OCEAN OBSERVING SYSTEM

3.1 - Overarching aspects

The fundamental issue is that global, comprehensive ocean (and other climate) data sets are needed for isolating and characterizing natural climate variations and to reduce uncertainty in estimates of climate change. GCOS (1998) developed the arguments around three basic premises.

(a) That climate change is a global phenomenon. Long time scales usually go with large space scales and, on the time scales of climate change, this implies global scales and global exchanges. Each gap in the global network will thus add uncertainty to our understanding and to estimates of change. These gaps are rarely the province of one nation and thus demand international cooperation in the implementation and maintenance of the network.

(b) That climate change involves interactions among all components. Following on from (a), we note that the time scales of climate change permit modes of interaction that most likely involve all components of the climate system (land, sea, air and ice). Our ability to recognize change will only be as strong as the weakest component of the climate observing system. For the oceans this means we should adopt an approach that gives appropriate emphasis to all variables, and that we explicitly take into account that the system must be implemented within the context of a global climate observing system.

(c) That priority must be attached to long records. The specific interest in temporal change implies we should value long, high-quality records above other aspects. Special care must be taken to preserve and nurture existing records and, where appropriate, efforts must be taken to establish new records so that future generations may have a more representative set of long-term records.

3.2 - Principal Objectives

With the establishment of the IPCC the climate change community has had a focus for assessment of climate change research and, indirectly, of the observing networks that contribute to this assessment. The Assessments (we are currently approaching completion of the Third Assessment) have also brought attention to the role of data sets in facets of climate change other than direct monitoring of change, such as detection and attribution and testing of climate models. One of the highest priorities for the Global Climate Observing System (GCOS) has been to establish long-term systematic observations in support of global and regional climate change and impact studies. The following objectives are drawn from GCOS (1998) and draw to a large degree on the deliberations of GCOS and its Panels and on the conclusions of the IPCC.

3.2.1 - *Characterizing current climate*

The significance of any assessment of change, be it looking backward or forward in time, is fundamentally dependent upon knowledge (characterization) of the present environment including the amplitude and scales of dominant modes of variability. Assessments such as those depicted in Figure 3 require a high-level of knowledge of the climate system. For the past we wish to filter out modes which, for the time scales of climate change, might reasonable be considered as "noise". We are mostly concerned with the underlying trend. For the future, we are likewise interested in projections for the trend but we realise this must be superimposed on expected levels of natural variability, the amplitude of which is likely to be several times that of the projected trend at any point in time. We now know the ocean plays a fundamental role in interannual climate variations and, that as a consequence, ocean observations are needed to better characterize the various modes which impact on its predictability. By analogy, we need to better characterize the oceanic manifestation of interannual and decadal climate modes that are likely to confound our attempts to interpret change. Isolating non-natural secular trends will demand high quality, comprehensive data sets. Moreover, just as seasonal-to-interannual prediction demanded not only air and sea surface observations but also upper ocean observations, we might expect climate change to place greater emphasis on deeper measurements.

3.2.2 - *Detecting climate change*

We wish to be able to identify statistically significant changes in climate against a background of natural

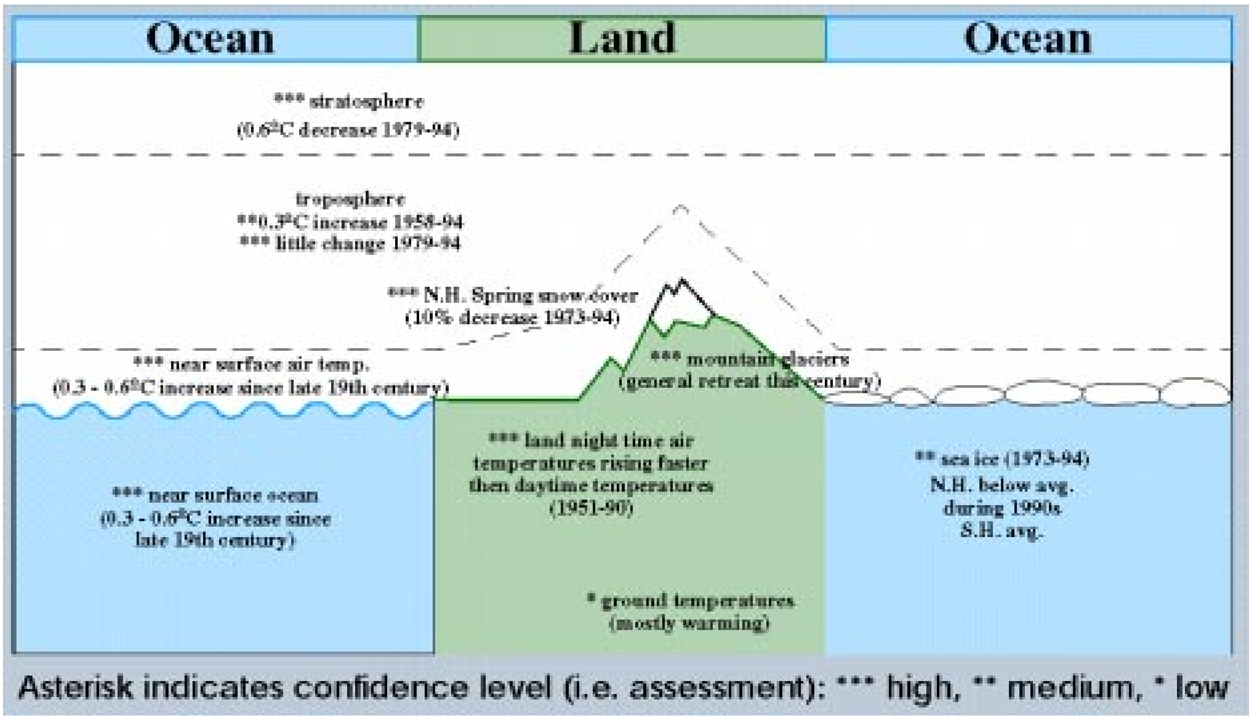

Figure 3. Schematic of the climate system showing conclusions from the 2nd Assessment (IPCC 1996). There is high confidence in the increase of near surface temperature and modest confidence in the assessed changes in sea-ice. Measurements of changes in deep water properties are too sparse to draw confident conclusions. Sea level change assessments (not shown here) are treated with modest confidence.

variability ("detect") and to be able identify the cause or causes of such change ("attribute"). Just as a doctor wishes to diagnose on the basis of a pattern of behavior and/or self-supporting symptoms, causes of climate change are thought best diagnosed through identification of patterns of change. If, for an assumed forcing, an hypothesised or predicted pattern is found in data then there is an increased likelihood that the observed pattern of change is due to that forcing. Such applications thus demand coherent climate data sets. Present models suggest we should expect an asymmetric response in the ocean, particularly in areas of deep water formation. Figure 4 shows some of the expected climate system perturbations. Our observing system must be capable of detecting such changes.

3.2.3 - *Forcing*

As noted in GCOS (1998), the most important measurements are those of the atmospheric constituents involved in radiative exchange (the "greenhouse gases"). The oceans are not expected to be a major

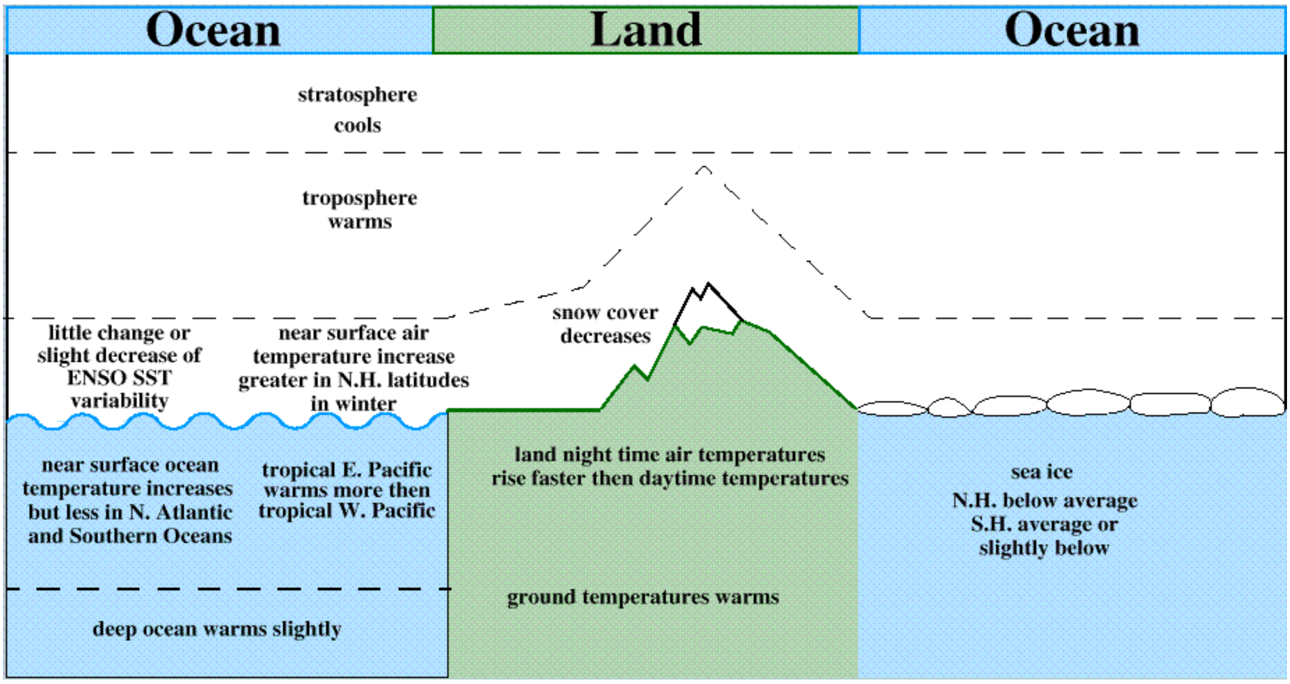

Figure 4. Schematic showing some of the expected changes in the climate system as predicted by models. Future generations need appropriate ocean data to test whether the suggested trends are being realised. For detection, a question arises as to how ocean changes might be optimally detected? Do we look in the deep on the premise that the signal to noise ratio will be favourable there? How many ENSOs do we have to measure through before we could detect a change in variability? These issues can only be addressed if we gather the appropriate data.

factor except insofar as they may be an important factor in the carbon budget and may be a source of radiatively important aerosols.

3.2.4 - *Model validation*

Clearly as models are used more and more for climate projections there is an overarching need to collect data needed to verify the models. Two modes are envisaged. First, as models are tested with observed forcing, long records are needed as a check for the generated time series. Can the model reproduce the observed variability? Second, since models are forced to parameterize much of the detailed observed interactions (e.g., air-sea fluxes, ocean eddies), data are needed to validate the processes and mechanisms of the model. Are the models reproducing observed deep-water formation mechanisms? Are modelled diffusion and mixing rates realistic?

3.2.5 - *Impacts of climate change*

Mankind is not directly sensitive to changes in the North Atlantic meridional overturning or a change in the strength of subtropical gyre. The impacts of climate change are likely to manifest as changes in the frequency and intensity of regional and local phenomena such as storms, coastal sea level, El Niño, etc. In other words, the consequences of climate change are likely to be felt in areas beyond the normal scope of a climate observing system.

4 - THE STRATEGY

It should be noted from the outset that the strategy is not based on the presumption that climate change due to anthropogenic influences exists. Rather, we adopt the view that there is sufficient concern about the impact of long-term variations in climate that we should implement measures now to ensure we are able to quantify whatever changes are taking place, be they small or large, of natural origins or not. To abrogate this responsibility will only exacerbate the current level of concern and uncertainty and leave this as a legacy for future generations.

4.1 - Overarching Principles

For climate change it is imperative that we promote observing methods and principles of data management that emphasize and value data quality, continuity, homogeneity, documentation and long records. Other papers in this Conference (e.g., Legler et al) discuss some of these issues in more detail. They are also discussed in Karl (1996). Three aspects deserve specific mention.

4.1.1 - *Data quality*

Data quality is not simply a matter of ensuring that platforms operate to specification and give clean data. For climate change the signals embodied in the data are likely to be small and delicate and thus require a scientific and technical appreciation of the methods used to collect the data. Knowledge of instrumentation and station and/or platform history is essential and should be treated with the same care as is accorded the data. This process is often referred to as the preservation of metadata but for climate change it warrants greater attention than for other applications of the ocean observing system

Experience within the World Ocean Circulation Experiment (again refer to Legler et al, this Conference) suggests quality checks should be performed as soon as possible after data collection since the amount of information readily available is usually at a peak at that time. For climate change this initial quality assurance often needs to be complemented by a more thorough scientific examination at some later time when it can be interpreted within the context of more comprehensive data sets and analyses. Unlike ocean prediction, where automated checking is the norm, climate change demands a high level of scientific involvement. The signals are sufficiently complex and delicate that models and encoded rules cannot be trusted as the last word on quality.

4.1.2 - *Continuity*

In this context, continuity refers to the consistency of measurement in time, avoiding changes in instrumentation and/or sampling rate that might compromise the ability to discern climate change. Experience has shown that it is all too easy to introduce spurious signals and/or bias through changed instrument algorithms and altered processing methods. We also compromise the value of the data set whenever gaps are introduced since the value of the data set for climate change depends critically on our ability to remove shorter-period variability; this cannot be done with surety if gaps comparable to the period of this variability are present.

We are also increasingly relying on remotely sensed data as part of our integrated observing system. Satellite platforms are at the high end of our technology and thus pose particular challenges with respect to platform-to-platform calibration and sensor stability. We are increasingly relying on the complementary contributions in the observing system to provide such calibration and to verify sensor stability and accuracy. The in situ sea level network (see Mitchum et al this Conference) and *Argo* (see Roemmich et al, this Conference) provide two forms of calibration for altimetry. Likewise, in situ measurements of SST (see Reynolds et al, this Conference) provide a calibration of radiance measurements. Conversely, remote sensing, because of its global coverage, provides ideal spatial calibration of in situ measurements that are rarely able to provide adequate spatial and global coverage.

4.1.3 - *Homogeneity*

This is in effect a generalisation of 4.1.2. Detection and attribution require resolution of space-time patterns spread over several climate variables. Any "gaps" in the relevant record will severely compromise our ability to detect change. In this context, "gaps" arise if either the space or time sampling is inadequate or if samples of the relevant fields are not available. We have already noted the inherent global character of climate change. The complexity of processes and scales implies that we must, to first order, attempt to maintain an even sampling and well distributed sampling density (in space and time) and cover those fields which are reasoned to be important for slow variation of the ocean. While it is possible in over-sampled regions to render the data set more homogenous by careful filtering and screening, it is usually impossible to fill gaps after the event.

4.2 - System evaluation

This aspect is introduced early because of its fundamental importance for climate change issues. Without organized and coordinated methods for monitoring observing system performance it is more likely than not that one of the aspects discussed under 4.1 will be compromised. All observing components face severe challenges because of cost constraints and logistics and we should always be seeking more effective and efficient ways to do things. However, climate change signals are at the extreme end when it comes to sensitivity to imperfect practices or inferior performance and so diligence must be exercised at all times. The Global Climate Observing System and Global Ocean Observing System were created with such issues firmly in mind. The value of data sets for climate change is not assured unless the data streams and observing practices are continuously monitored and checked against the recommended benchmarks.

The performance measures must be set with extreme care since costs tend to rise rapidly with unduly conservative practices and over-designed networks. This balance cannot be easily prescribed and we tend to rely on the oversight bodies within GCOS and GOOS to ensure that standards are being kept. There are several examples in this Conference where studies have been undertaken with the specific intent of ensuring that the observing system is performing efficiently and effectively. The evaluations invariably address issues of data management as well as the data themselves. Often, it is the communication and delivery of information that is under-performing rather than the measurement system itself.

4.3 - An integrated observing system

Other papers in this Conference will discuss in more detail the importance of an integrated observing strategy within the general context of ocean observations (Nowlin et al; Ratier et al). As noted previously, the complex nature of the climate system for long-term change makes it essential those issues of comprehensiveness, completeness and integration are addressed up front. The Integrated Global Observing Strategy (IGOS) is one manifestation of the community's determination to ensure such issues are adequately addressed.

4.4 - The role of models and data assimilation

Models and data assimilation are the catch-cry of this generation of oceanographers. Clearly, when we view progress in meteorology and consider the complexity of the ocean data sets being collected, it is no longer feasible to avoid non-trivial analysis techniques. Smith (1993) discusses some of these issues and notes the significant challenges. However a degree of caution is warranted.

Meteorology has undertaken several re-analyses of available meteorological data (e.g., Kalnay et al., 1996). These efforts have made enormous contributions to climate science yet, despite all such efforts, significant issues remain (GCOS 1998). Long-term climate signals are delicate. The processing of data using data assimilation and models involves many complex phases, none of which are perfect. The projection of the data onto the model fields involves assumptions; the model is discrete and built upon many parameterizations; the data assimilation involves a further set of assumptions and parameterizations; add to that the general paucity of data for long-term problems and there is little wonder models struggle to eradicate biases. If we must treat atmospheric model estimates of trends with caution, then it should not come as a surprise that ocean analyses are treated with a deal of scepticism. We are poorer in terms of data, models and knowledge of the key parameterizations. This does not mean we cannot learn a great deal from inversions of ocean data (see, e.g., Stammer et al, this Conference) but that, when it comes to detecting climate change we should be wary of introducing processing elements that might (will) introduce biases and spurious signals at least as large as the ones we wish to detect.

5 - THE CURRENT ASSESSMENT

In this section we introduce a few examples which suggest that the ocean is undergoing change on long time scales and that this change might be partly attributed to anthropogenic effects.

5.1 - The IPCC

The Intergovernmental Panel on Climate Change (IPCC) was created because of the widespread concern about the so-called "greenhouse effect" and has undertaken a series of assessment of climate and climate change (Houghton et al 1992; Houghton et al 1995). The Third Assessment is currently in progress. The IPCC has been extremely influential both because of the central role it is playing and because it has entrained/involved scientists from the very highest levels. The assessments of the IPCC are held in very high respect among the scientific community. The process of authorship and review for the present Conference is a miniature of the procedures agreed by the IPCC.

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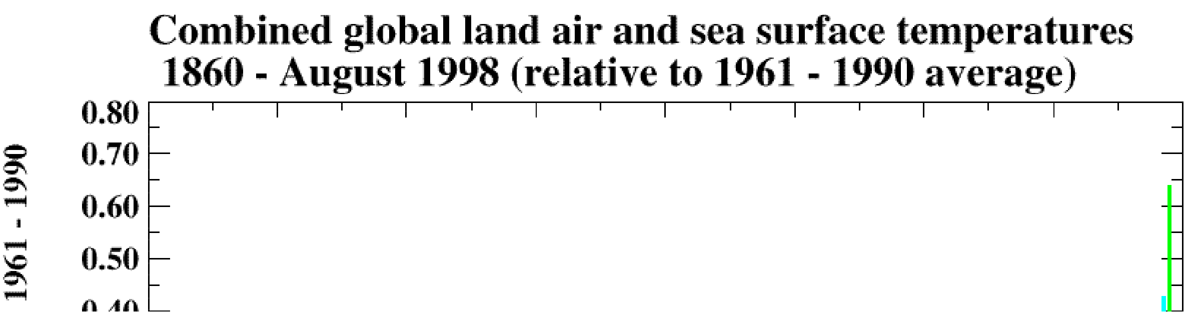

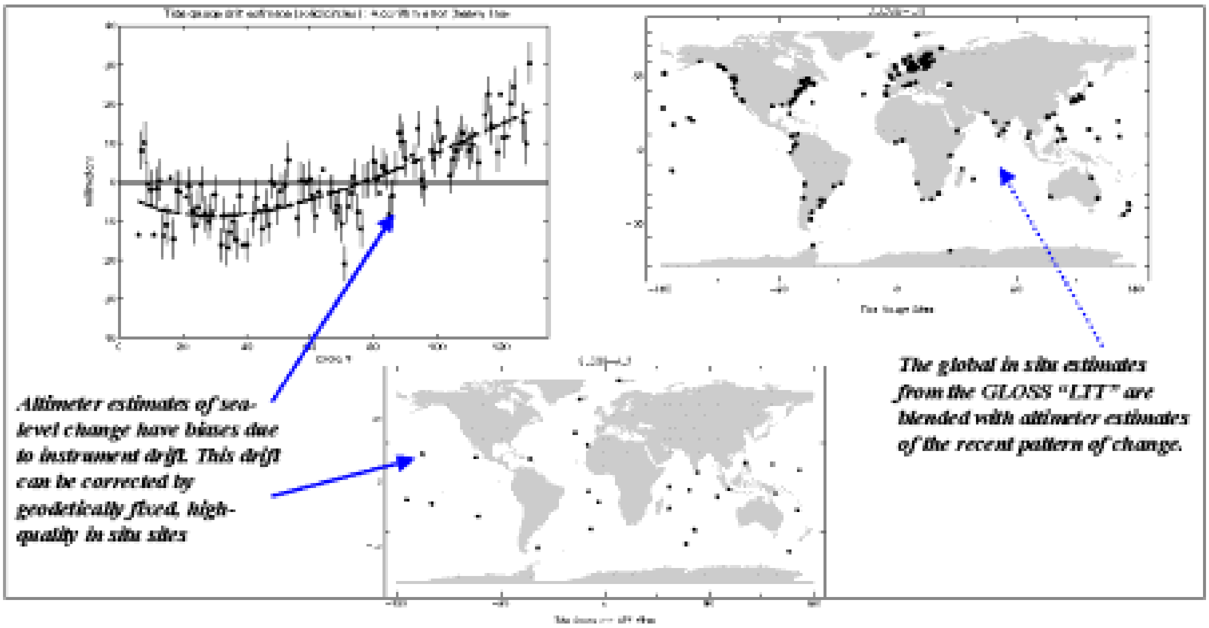

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Figure 5. Combined global land-surface air temperature anomalies and Sea Surface Temperature anomalies (°C) 1861

Figure 6. Schematic showing the way satellite altimeter estimates of sea level change are blended with data from tide

pattern of change; the gauges tie down the absolute change and provide a knitting with the past. The conclusions with respect to thermal expansion are also like to be important. The need for deep ocean data for climate change is discussed in depth in Gould, Toole et al (this Conference).

6 - CONCLUSIONS

This paper provides an overview of some of the main issues related to climate change and ocean observations. GCOS (1998) brought many of these issues to the notice of the broader community and we are now in the position of being able to suggest mechanisms whereby the inadequacies of the present observing system might be addressed. We note that the sources of uncertainty in present appraisals of climate change and future scenarios are due in part to our lack of ocean data. Delineating trends in ocean analyses depends upon thorough knowledge of the variability on shorter time scales so, in a sense, there is an inextricable link between climate change observations and observations of all other ocean phenomena. The strategy should place a high premium on data quality, continuity and homogeneity. It is also critical that the observing system for the ocean is properly integrated with other components - climate change is not just manifested in one or the other but involves coupled change. We suggest deeper measurements are likely to have greater importance but with the cautionary note that the advantages offered by a favourable signal-to-noise ratio might not replicated in surface fields.

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