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THERMOHALINE CIRCULATIONS AND GLOBAL CLIMATE CHANGE

[DOE Grant No. DE-FG03-93ER61646]

Annual Progress Report No. 1

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Overview

This report discusses research activities conducted under the auspices of DOE Grant No. DE-FG03-93ER61646 since its inception on 15 July 1993. The previous grant, DE-FG02-90ER61019 (of the same title), is currently operating under a no-cost extension, so that this report also discusses activities conducted thereunder.

Background

The original project entitled "Thermohaline Circulations and Global Climate Change" was concerned with investigating the hypothesis that changes in surface thermal and hydrological forcing of the North Atlantic, changes that might be expected to accompany CO_2-induced global warming, could result in ocean-atmosphere interactions' exerting a positive feedback on the climate system. Because the North Atlantic is the source of much of the global ocean's reservoir of deep water, and because this deep water could sequester large amounts of anthropogenically produced CO_2, changes in the rate of deep-water production are important to future climates. Since deep-water production is controlled, in part, by the annual cycle of the atmospheric forcing of the North Atlantic, and since this forcing depends strongly on both hydrological and thermal processes as well as the windstress, there is the potential for feedback between the relatively short-term response of the atmosphere to changing radiative forcing and the longer-term processes in the oceans.

Work on this hypothesis led to a second line of investigation, which has become a new focus for the new award discussed here. The sensitivity of the annual cyle of the upper ocean to variable atmospheric forcing also determines the structure of the seasonal thermocline, and consequently it is necessary to include both synoptic-scale and interannual variability of atmospheric forcing to fully understand the potential effects of long-term trends of that forcing. Due to its large heat capacity and its nonlinear response to forcing, the upper ocean *rectifies* the forcing by radiative fluxes, turbulence, and windstress, creating responses on much longer time scales than those of the forcing.

This report focuses on recent work oriented toward this problem that was a source of criticism during the review process on the most recent proposal: the quality of the upper ocean model being used in the investigation. Other recent progress is also reviewed.

Mixed-Layer Alternatives

MICOM integrations

The Miami Isopycnic-Coordinate Ocean Model (MICOM—as it has become to be known) was originally formulated purely in isopycnic coordinates and used to investigate the ocean's response to windstress forcing. Because isopycnic coordinates—i.e., coordinates using water density rather than depth or pressure in the "vertical"—are effective only in adiabatic flows, extending the model to simulate a complete, thermodynamically active ocean required the development of a hybrid approach that added to the top of the isopycnic model an upper-ocean formulation capable of exchanging heat with the overlying atmosphere. This had been done previously by various investigators, but their approach has been to use a constant-depth mixed layer for the thermodynamic module. Bleck, Hanson, Hu, and Kraus [1989 *J. Phys. Oceanogr.*, **19,** p. 1417ff] were the first to develop a hybrid isopycnic–mixed-layer model that attempted to simulate correctly the physics of upper-ocean mixing. This was accomplished by developing algorithms to match the Kraus-Turner mixed layer model (in the form outlined in Niiler and Kraus [1977 *Modeling and Prediction of the Upper Layers of the Ocean*, Pergamon, p.143ff]) to the pure isopycnic model described by Bleck and Boudra [1981 *J. Phys. Oceanogr.*, **11,** p. 755ff; and 1986 *J. Geophys. Res.*, **91,** p. 7611ff].

While providing a simple and elegant solution to the complex problem of upper-ocean mixing, the Kraus-Turner model is not without its shortcomings; many of these are described in the work of Gaspar [1988 *J. Phys. Oceanogr.*, **18,** p. 161ff], and reviewers of both of the proposals associated with this project were quick to point this out. To address this issue, the model has been reformulated using Gaspar's algorithm, and comparison integrations have been run. It should be emphasized that Gaspar's formulation is based on a more realistic treatment of dissipation in the upper ocean, but that the basic mixed-layer approach to the problem is retained. Gaspar's formulation also involves seven adjustable parameters, compared to two in the original Kraus-Turner approach. The main advantage, as seen below, of the Gaspar formulation is to reduce the penetration of the winter mixed layer to less of the water column, so that the seasonal thermocline is shallower than in the Kraus-Turner approach.

Figures 1 illustrate this clearly. The two panels compare identical runs of the MICOM using the Kraus-Turner mixed layer (top) and the Gaspar approach (bottom). Over the six years of integration illustrated, wintertime mixed layers are shallower at all latitudes in the Gaspar run. Note also that summer mixed layers are actually deeper in the Gaspar run. This combined result is due to the effect of variable dissipation in the Gaspar formulation: wind mixing is more efficient when the layer is shallow and is less so for deep layers. As discussed in the Gaspar paper, this is also more realistic. Figures 2 illustrate the model differences more clearly at a single latitude. The vertical coordinate in Figs. 2 is temperature, and the annual cycle of the mixed layer is shown as the top-most curve. The seasonal thermocline appears as the cluster of isotherms just under this top-most curve when the mixed layer is shallow. The reduced amplitude of the annual cycle is evident in the Gaspar run.

From this comparison, it may be concluded that there are significant differences in the two approaches, and that it may be preferable to adopt the Gaspar approach for climate studies using the MICOM. It is important to bear in mind, however, that this is a comparison between two model runs and that there is no real-world calibration involved. Because long-time series of the details of upper ocean structure are scarce, limited to a few measurements at the sites of specific oceanographic moorings, alternative approaches to comparing model results to datasets are indicated.

Phase diagrams

While detailed observations of the annual cycle of upper-ocean structure are relatively scarce, surface observations are available for virtually all of the world ocean; these have been compiled in the Comprehensive Ocean-Atmosphere Data Set (COADS). COADS observations include monthly averages of surface observations, culled for bad data, and binned into two-degree squares. Surface thermodynamic fluxes and windstresses can be calculated from this data. In addition, COADS has been used by a variety of investigators to deduce radiative fluxes, using empirical formulae.

From an oceanographic perspective, the two most important thermodynamic quantities for climate studies are the sea-surface temperature and the net surface heat flux. In the ocean-surface heat budget, the latter is the dominant term. That is, defining H_n as the net surface heat flux, h as the mixed layer depth, T_s as the sea-surface temperature, and t as time, the surface heat budget can be written symbolically $\partial T_s/\partial t = f\,(H_n, h, ...)$, with H_n the largest term on climatological scales. Therefore, constructing a diagram of H_n vs. T_s is equivalent to a partial construction of a diagram of dT_s/dt vs. T_s. This representation of the behavior of a dynamical system is the construct familiar to electrical engineers and others as a *phase diagram.* For studies of periodic phenomena, as well as stability analyses, these diagrams provide a wealth of information about system behavior, particularly phase lags between the state variable (in this case, T_s) and its forcing. and its approach to, or divergence from, stable states.

The loop in Figure 3 shows H_n (expressed as oceanic heating) plotted vs. T_s for COADS observations at Ocean Weather Station C in the North Atlantic, with the solid circles representing individual monthly observations. Beginning in January (the solid circle to the lower left), the month with the most oceanic cooling and with almost the lowest T_s, the annual cycle proceeds clockwise toward August (right-most solid circle), with the highest T_s. The deeper winter mixed layers cause a greater time lag of increases of T_s than do the shallower mixed layers of T_s decreases, as can be inferred from the more rounded character of the loop on its left end compared to the right end. Although the T_s and H_n scales change, this general pattern holds for COADS data at most latitudes in the North Atlantic.

The OWS C COADS result is reproduced in both panels of Figures 4, along with results from several mixed-layer models subjected to smoothly interpolated monthly forcing. In all cases, these results are derived from integrations of a one-dimensional version of the MICOM with the various mixed-layer modules used. An imposed horizontal advection of heat, with annual cycle derived from the work of Lamb and Bunker [1982 *J. Phys. Oceanogr.*, **12**, p. 1388ff], was used to adjust the annually averaged temperature of each integration to that of the COADS observations.

The various constant-depth models in the top panel of Fig. 4 bear little resemblence to the observations. They also imply the behavior of such a model in its two limits. As $h \rightarrow \infty$, the "loop" would become a vertical straight line, with no variations in T_s, and with H_n controlled entirely by the varying atmospheric forcing. As $h \rightarrow 0$, the loop would nearly collapse, because

T_s would respond instantly to forcing and there would be no hysteresis due to time lags. From these various loops, it can be inferred that a constant-depth layer of about 150 m would approximately reproduce the temperature range of the observations, although the phase would be wrong.

In the lower panel of Fig. 4, the Gaspar and Kraus-Turner formulations are compared with the 100-m constant-depth model and with the observations. All-in-all, the Kraus-Turner model most closely resembles the observations. All three models, however, fail to simulate correctly the observations during the spring heating season; this is the time when the seasonal thermocline forms and is therefore the crucial time of year for the research here. Note in Fig. 2 that this incorrect simulation of mixed-layer retreat in the spring is associated with a very thin and highly stratified seasonal thermocline just under the shallow summer mixed layer. While either the K-T or the Gaspar model will result in injection of ventilated, mixed-layer water into the permanent thermocline eventually, the rate of injection and the properties of the injected water are not being correctly simulated by these mixing parameterizations. Work completed and in progress is examining the role of synoptic-time-scale weather disturbances in modifying this modeled behavior and producing a more correct simulation.

Discussion

Several conference contributions discuss various aspects of the work reviewed above:

• The role of simulated synoptic-time-scale variations in the wind speed (which controls both wind mixing and the turbulent thermodynamic fluxes in the mixed-layer model) in modifying the formation of the seasonal thermocline was discussed in a poster by Hanson and Bleck at the Third Scientific Meeting of The Oceanography Society in Seattle (April, 1993); this was entitled "Rectification of Atmospheric Forcing by the Oceanic Mixed Layer."

• The model comparisons, with extension to variable atmospheric forcing on both synoptic and interannual time scales, will be discussed at the 1994 Ocean Sciences Meeting of the American Geophysical Union (San Diego, February, 1994), in a paper by Hanson entitled "Modeling Climatological Heat Storage in the North Atlantic Ocean."

• The response of the MICOM to the different mixed-layer formulations will be discussed at that same Ocean Sciences Meeting in a paper by Halliwell, Horsfall, Bleck, and Hanson entitled "Sensitivity of an Isopycnic-Coordinate OGCM to Parameterizations of Upper-Ocean Mixing."

• One important aspect of the initial hypothesis motivating this project will also be discussed at the 1994 Ocean Sciences Meeting in a paper by Horsfall, Bleck, and Hanson entitled "Variation of the Subdiction Rate in Response to Global Climate Change." Ms. Horsfall, a graduate student at the University of Miami supported by the subcontract of this award, passed her Ph.D. qualifying examination in October, 1993, and is now in the most productive stage of her research.

• In January, 1994, Prof. Rainer Bleck (the Co-PI on the project, and the PI of the University of Miami subcontract) will host a workshop to discuss various aspects of the MICOM, including many relevant to this project. The results discussed above and at the various other meetings will be presented at this workshop, and issues such as standardizing the model and its output modules will be discussed as well.

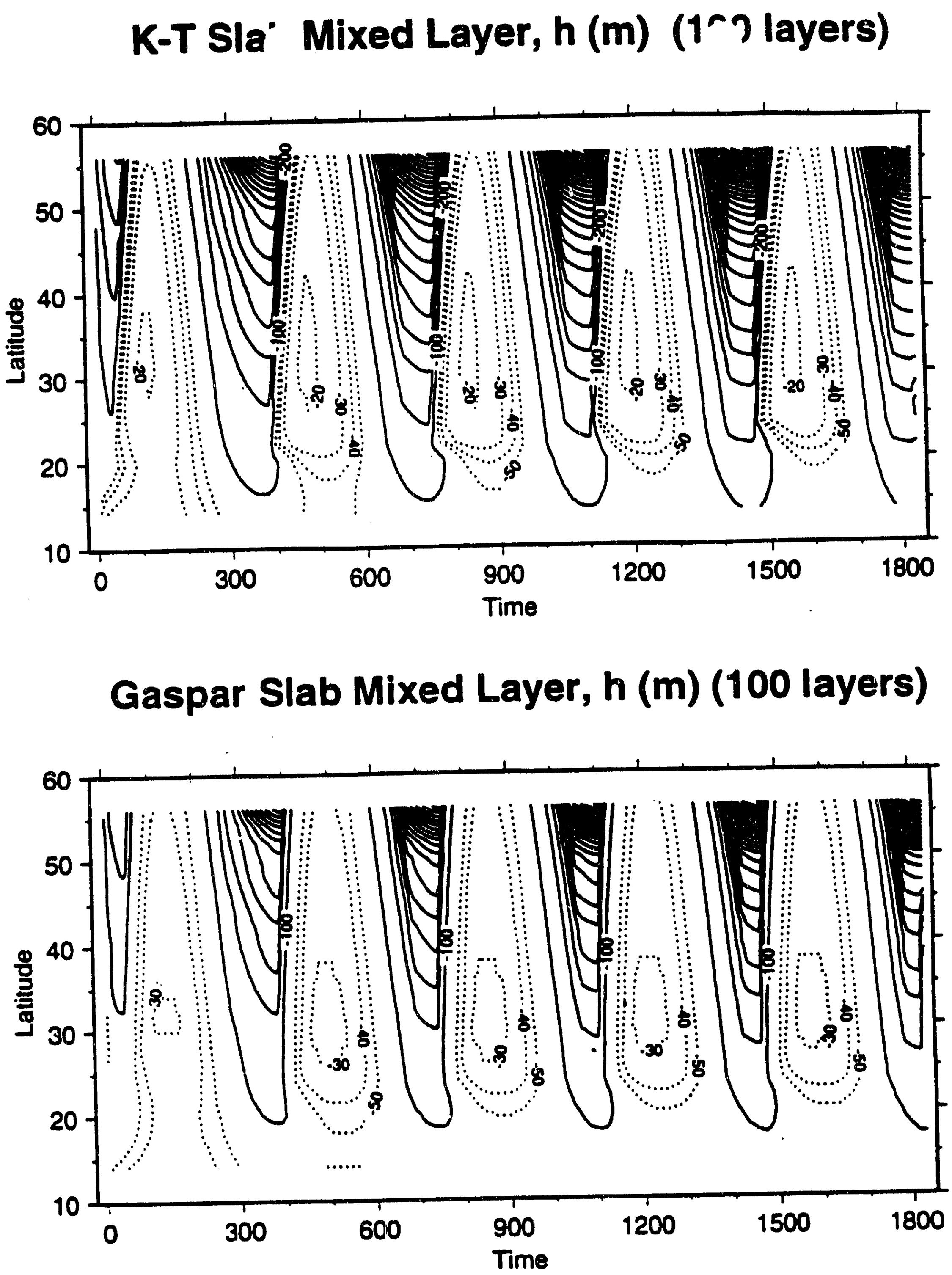

Figure 1. Comparison of mixed-layer depths in the MICOM over six years of integrating an annual cycle (time scale is in days) as a function of latitude. Gaspar formulation (bottom) produces less extreme swings in mixed-layer depth than does the Kraus-Turner approach (top).

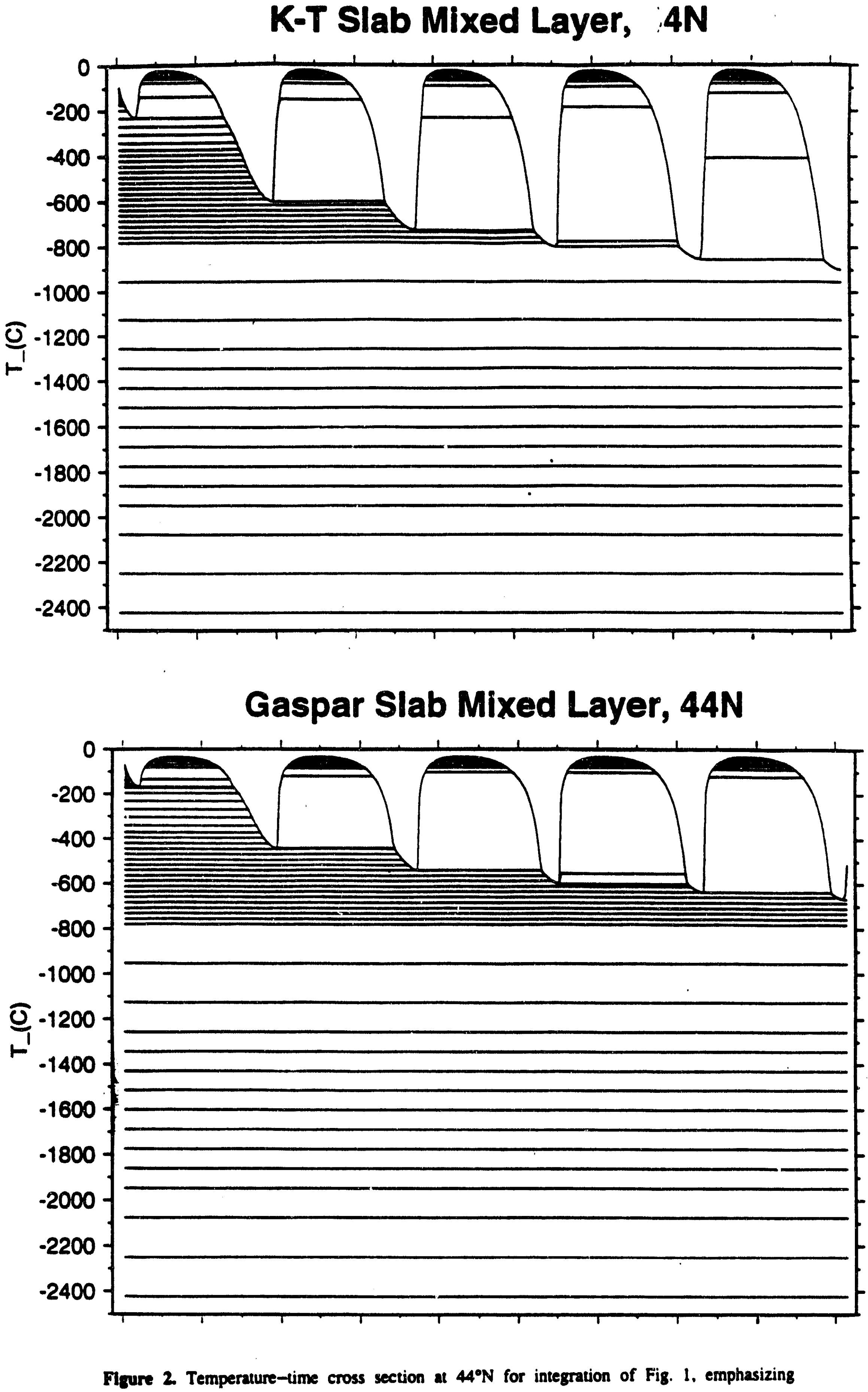

Figure 2. Temperature–time cross section at 44°N for integration of Fig. 1, emphasizing moderated annual cycle of the mixed layer in the Gaspar formulation.

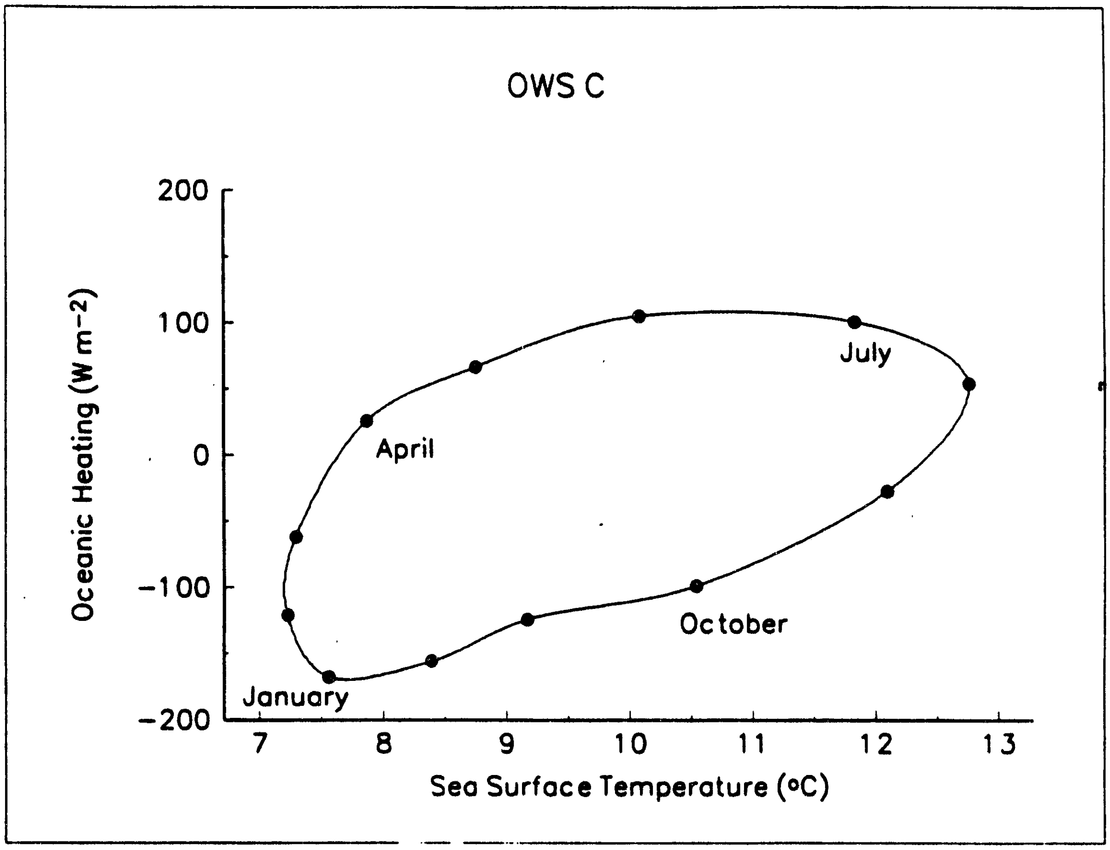

Figure 3. Partial phase diagram of net surface flux (expressed as oceanic heating) vs. sea-surface temperature for COADS observations at the location of Ocean Weather Station C.

DISCLAIMER

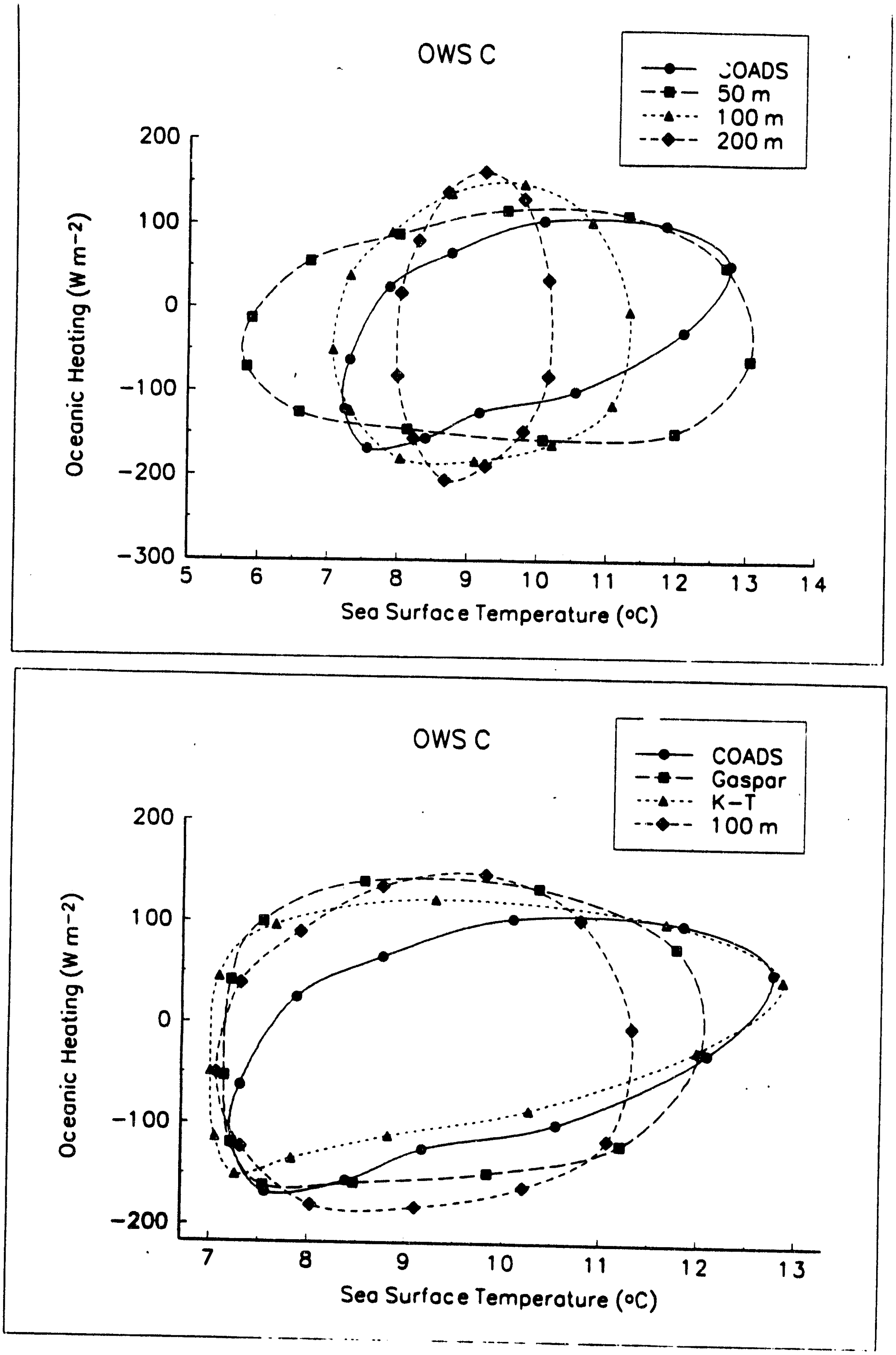

Figure 4. As in Fig. 3, for various mixed layer models forced by a smoothly varying annual cycle, and for COADS at the location of Ocean Weather Station C. Top panel compares various constant-depth mixed-layer models; bottom panel compares the 100-m constant depth model with the Kraus-Turner and Gaspar models. Note that the Kraus-Turner model provides the best simulation of the COADS observations.

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