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Woods Hole Oceanographic Institution

Biological/Physical Modeling of Upper Ocean Processes

by

Cabell S. Davis and John H. Steele

September 1994

Technical Report

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Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

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Approved for Distribution:

Joel C. Goldman, Chair
Department of Biology

WORKSHOP REPORT:

BIOLOGICAL/PHYSICAL MODELING OF UPPER OCEAN PROCESSES

Sponsored by: University Research Initiative Program (URIP),
Office of Naval Research (ONR)
(Grant No. ONR-URIP N00014-92-J-1527)

Date: June 7–12, 1993

Location: Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA

Conveners: Cabell S. Davis and John H. Steele

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1. Introduction

In order to increase communication between investigators who are modeling upper ocean biological/physical processes, a workshop was convened in Woods Hole on June 7-12, 1993 (see Appendix I for names and addresses of participants). This workshop was part of our on-going URIP project entitled "Modeling Biological-Physical Interactions: A Population Biological Approach" sponsored by ONR (Grant N00014-92-J-1527). The two principal goals of the workshop were to: 1) identify critical problems related to mixed-layer biological-physical models, and 2) develop approaches for solving these problems.

The workshop was organized into two parts to address these goals. The first part, held over the first day and a half, included three overview presentations given in plenary followed by working groups, organized along disciplinary lines, to identify critical issues. The second part of the workshop consisted of working groups, organized across disciplines, using "hands-on" modeling to address critical aspects of coupled biological-physical models.

Overview presentations were given during the first morning to provide background information on physical mixed-layer models (Kenneth Denman), biological models with age-structured herbivore populations (John Steele), and microbial-loop dynamics (David Caron). Following these presentations, the working groups were organized to address problems associated with 1) physical modeling, 2) structured herbivore vs bulk nutrient-phytoplankton-zooplankton models, 3) food-web models, and 4) coupling complex biology to 2- and 3-D physical models.

After plenary reports of these first-format working groups, the second-format working groups were formed to begin modeling in the areas of 1) coupling simple food-web models to several different physical models, 2) development of NPZ models which include microbial-loop dynamics, and 3) development of structured-zooplankton models and incorporation into NPZ models.

An annotated bibliography of existing mixed-layer models was provided by David Archer and is given in Appendix II. Brief descriptions of three coupled biological/physical mixed layer models is given in Appendix III.

2. General Reviews–Critical Issues (from 1st-format Working Groups)

2.1 *Physics of Mixed Layers*

Archer, Chen, Denman, Doney, Gawarkiewcz (Rapporteur), Glover (Chair), Hood

- The biological questions which are being addressed should affect the choice of model being used.
- Models have clearly defined weaknesses which must be taken into consideration before use. For example, P-W-P assumes no vertical velocity shear is present in the mixed layer, while observations show such shear is frequently present.
- We should be thinking about upper ocean models in general (i.e. including the thermocline) rather than strictly limiting ourselves to calculating the "mixed layer depth". This is particularly important when considering heat flux divergences in 1-D models (what depth do you "advect" the heat away when modelling an annual cycle?). Lateral mixing processes may be important in the thermocline in distributing nutrients

along isopycnals. The vertical transport of nutrients into the base of the mixed layer needs to be considered.

- Observations of Jenkins clearly show an enhanced vertical flux of nutrients into the euphotic zones which current models using standard parameterizations cannot explain. Is this due to mesoscale variability and eddy pumping? What should be done with 1-D parameterizations if mesoscale effects are important?
- What role do large and small-scale fronts play in understanding mixed layer dynamics? How important are horizontal inhomogeneities in understanding the performance of 1-D models when compared with time series of observations? How should mixing within frontal zones be parameterized? More observations with good horizontal resolution will be necessary to make progress in this area.
- What level of complexity is needed in prescribing optical fields? Under what conditions do the absorption characteristics affect the temperature distributions in the vertical?
- There are major questions regarding the Lagrangian descriptions of flow fields in the upper ocean. In particular, the Lagrangian behavior of particles in fields where the mixing coefficients are changing with depth is not well understood. Good Lagrangian information is necessary to describe light histories of particles as well as predator-prey contact rates.
- How will the use of Large Eddy Simulations affect our understanding of the mixed layer? These models seem to give results that are very different from both P-W-P as well as Mellor-Yamada Level 2.5.
- The integration of data from various acoustic observational techniques which resolve the turbulent eddies in the mixed layer should lead to much better parameterizations of the characteristics of the turbulence. Hopefully, this will occur over the next 5 years or so.
- In the coastal regions, the interaction of the bottom and surface boundary layers is not well understood. Much more work in the future will be necessary to resolve this issue.
- Surface forcing in regions in which no buoy data is available is a major problem. Wind products tend to severely underestimate maximum wind velocities, which leads to major differences in surface fluxes.
- Processes associated with the surface wave field are not included in most present day mixed layer models. The effects of Langmuir cells and wave dissipation on the turbulence fields will have to be addressed in the future.

Conclusions

- Horizontal variability is not well known.
- Lagrangian nature of flows are not well known.
- Acoustic observational techniques will help resolve turbulence fields.

2.2 *NPZ vs NP-(Structured-Z)*

Armstrong, Bollens, Caswell (Chair), Frost, Lewis (Rapporteur), Steele

- Why structure only herbivore populations?

- No reason, in fact the group decided in many cases that structure could be required in a number of different trophic levels.

- What is the purpose of structure?
  - This was one of the primary questions that came around, as it is possible to add structure to a wide variety of populations and trophic levels while accomplishing nothing more than tying up your computer. Applications in which stage-structured models may be needed include:
  - Fisheries models in which it is necessary to know the abundance of a wide variety of zooplankton species; prey for the larval fish.
  - Data comparison and validation. However, the converse of this is that there is little point in running a stage structured model where you have no information concerning the population structure.
  - For comparison to NPZ models to determine whether the introduction of stage structure has a significant effect on the dynamics.
  - To introduce stage specific behavior.
  - To represent the microbial loop and other multispecies models.
  - Time scales of response by a species with a long growth period may require stage structure to be adequately represented.
  - Abundances may respond with a periodicity determined by the generation times.
- Problems with such stage models include:
  - You may need multiple phytoplankton populations to support a multi- species grazing population.
  - Truncation of the trophic models to the highest trophic level of relevance.
- Vertical structure:
  - Need the physical dynamics to transport plankton, but you may not need a full one-D biological model to couple to the physics.
  - Behavioral effects.
- Incorporation of physical models.
  - May not need full resolution of PWP model.
  - Should explore sensitivity of models to increased physical complexity.
- Suggestions:
  - Use output of physical model to drive biology: use temperature and diffusivity values, time-smoothed
  - Time smooth and space smooth spatial model at varying scales to determine what effect the reduced complexity will have on the biology.
    - Use 100 point PWP results on 100,50,20, etc. level biological model.
    - Use time averaged PWP fields, determine effect of high frequency activity.
  - Combine the organisms of Caron's work with the model written by Armstrong.

2.3 *Food web models and validation with data*

Caron, Landry (Chair), Landsteiner (Rapporteur), Moisan, Sarmiento

- Critical Task:
  - Implementation of food-web models with appropriate microbial community structure and interactions.

- Minimal structure of a microbial loop model:
  - Three phytoplankton (pico, nano, and micro)
  - Heterotrophic bacteria
  - Two levels of protozoan consumers (nano and micro)
  - DOM flows from phytoplankton excretion, sloppy feeding, decay of protozoan feces, and mortality.
- Relevance of microbial dynamics in food webs: - Basic structure of lower trophic levels in all upper ocean environments.
  - Allows partitioning of primary production among size classes, a major distinguishing characteristic of different environments or seasons.
  - Essential to understanding the basic mechanisms of phytoplankton control (i.e., grazing vs nutrient limitation).
  - Provides a realistic resource environment for modeling of macro-consumers.
  - Provides a versatile format for other desirable model outputs:
    - new production ratio (recycling pathway)
    - multi-elemental cycling
    - vertical fluxes (sinking vs. non-sinking feces)
- Necessary and existing data:
  - standing stocks and elemental composition of all populations
  - size-fractionated primary production
  - protozoan grazing rates and behaviors
  - protozoan growth efficiencies
- Problems:
  - Thresholds
  - Closure through metazoans (multiple species and stage-structure)
  - Allometric relationships
  - Depth structure (controlled through light and nutrient kinetics)
  - Selective feeding on multiple-size classes

2.4 *Problems in use of 1-D coupled biological/physical models*

Davis, Flierl (Chair), Franks (Rapporteur), Levin, McGillicuddy, Olson

- Critical Issues
  - Horizontal advection necessary over long time-scales to balance deep heat flux, nutrient flux
  - Timescales of mixing in the model vs. biological rates - how to parameterize faster rates (e.g. photoadaptation) in mixed layers
  - How to parameterize patchiness and variability of biological fields
  - How does variance propagate trophically, temporally - can we use statistics of biological distributions as variables in the model?
  - When is use of PWP model appropriate?
    - short-term variation in seasonal thermocline; days-weeks
    - if coupled to "good" GCM, may be able to extend its usefulness

- need to consider importance of remnant layers to vertical fluxes over long times scales. May necessitate forced boundary conditions, or coupling to 2-D or 3-D PE model.

- Suggestions:
  - use a number of different models of the same physical/ biological problem (sensu Martin) to assess utility, and observe differences.
  - use large-eddy simulation models for more realistic 2-D or 3-D representation of smaller scales
  - use Deardorff-type model (4th order closure) rather than PWP

3. Reports of Work (2nd format Working Groups)

3.1 *Comparing mixed layer models containing simple plankton dynamics*

Chen, Denman (Chair), Doney, Flierl, Franks, Gawarkiewcz, Glover, Hood

3.1.1 *Goal*

To compare the behavior of several models of mixed layer physics coupled to simple Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) models.

3.1.2 *Physical Mixed layer models*

The group concentrated primarily on completing the comparison and coupling of mixed layer models to a simple NPZ model, all set up beforehand by Glenn Flierl. In addition S. Doney and D. Glover set up a mixed layer model being developed at NCAR with an NPZD model, and R. Hood explored the behavior of an NPZD model coupled to CONV and PWP (described below). The following mixed layer models were included in the comparison:

- CONV - This model was the simplest, consisting of a mixed layer depth of 10 m or else one determined by simple convective adjustment, whichever was deeper. Each day at noon, the mld retreated to 10 m and each night it reached a depth ranging from about 20 m in summer to 80 m for 1-2 months in the winter (which was the bottom of the model). The annual cycle was more realistic than in the plots to follow, which track the mld at midnight, several hours before the deepest mixing each night.
- PWP (Price-Weller-Pinkel) - This model consists of a mixed layer where the buoyancy is mixed completely each time step (Price, Weller and Pinkel, 1986). The thickness of the mixed layer is determined by a bulk Richardson number closure ($Rb \geq 0.65$), followed by a smoothing below the mixed layer to relieve any shear instabilities such that the local gradient Richardson number $Rg \geq 0.25$. This version, coded by Jim Price and modified by Glenn Flierl, also has an option for a background diffusion which was not used except by R. Hood who was using a version modified by Hood and Olson to correct problems with the coding of the background diffusion.
- MY (Mellor-Yamada) - This model is based on a level-2 turbulent closure scheme outlined in Mellor and Yamada (1974) and first implemented by Mellor and Durbin (1975). The vertical mixing at any depth is determined by a turbulent eddy coefficient that is a function of the mean turbulent kinetic energy (TKE), a length scale taken to

be the first moment of the TKE, and a stability coefficient that is calculated according to some laboratory-determined empirical equations that are functions of the local flux Richardson number Rf. Thus, an output of the model is a vertical profile of the coefficient of vertical turbulent diffusion of heat, $K_T(z)$, which is the key output for coupling with a biological model. This version, coded by Patrice Klein and modified by Jim Price, also has a constant background diffusion.

These three models were set up for the workshop by Glenn Flierl, with a common module for wind and heat forcing and a common biological NPZ module for coupling. A simple-to-use set of plotting commands was also set up so that comparison on common axes at the same size could easily by made.

- NCAR - This model was implemented and coupled to an NPZD at the meeting by S. Doney and D. Glover. This is a one-dimensional coupled biological–physical model built at NCAR as the first part of a longer term project for developing a 3-D, global coupled model. The physical model, which is based on models of the atmospheric planetary boundary layer, differs from existing ocean models, and a complete description can be found in Large et al. (1993). The model is a non-local parameterization of the oceanic boundary layer based on the concept that the profiles of eddy diffusivity in the planetary boundary layer (either atmosphere or ocean) are similar in shape if the appropriate scaling is applied (boundary layer depth, surface wind stress and surface buoyancy flux). The shape parameterization used in the model is based on Large Eddy Simulation (LES) results (Deardorff, 1972). Constraints are also applied to the parameterization such that the eddy diffusivity in the surface layer matches the results of similarity theory. The depth of the ocean boundary layer depth is computed based on a bulk Richardson number criteria.

  The physical model can be run using either prescribed surface fluxes or atmospheric state variables (e.g. air temperature and humidity, wind speed); atmospheric forcing can be either specified using simple harmonics or read in from a data file. The daily cycle of solar radiation is computed using a geometric solar model and the cloud model of Smith and Dobson (1984).

3.1.3 *Biological models*

The NPZ model set up on the computer by Flierl for coupling to the mixed layer models was a relatively simple model with some non-standard terms such as the extra P factor in the grazing term (to replace a threshold value in the Ivlev formulation), the Michaelis-Menten phytoplankton growth dependence on light, and the Z^2 dependence death term for the zooplankton. The model consisted of the following equations:

$$\frac{DP}{Dt} = V_m \frac{I_0(t)I(z)}{I_0(t)I(z)+\beta} \frac{N}{k_s+N} P - R_m \lambda P Z[1-\exp(-\lambda P)] - bP$$

$$\frac{DZ}{Dt} = \gamma R_m \lambda P Z[1-\exp(-\lambda P)] - dZ^2 \tag{1}$$

$$\frac{DN}{Dt} = -\frac{DP}{Dt} - \frac{DZ}{Dt}$$

where I(z) is the light intensity function

$$I(z) = \exp(z/\beta_2)$$

The surface light intensity $I_0(t)$ varied with time of day and season. Parameters values and initial conditions are given in Table I.

Table I. Parameter values used in the NPZ model set up by Glenn Flierl

Parameter	Value	Description
I	—	irradiance
V_m	2.0	maximum phytoplankton growth rate
k_s	0.1	nutrient half saturation coefficent
R_m	0.35	maximum zooplankton growth rate
λ	1.0	Ivlev coefficent
b	0.05	phytoplankton mortality
γ	0.7	egestion fraction
d	0.2	zooplankton mortality
β	0.5-1.5	light half-saturation coefficient
β_2	20.	light e-folding depth
State Variables:	$P_0 = 2.7$ $Z_0 = 0.35$	$N_0 = 1.95$

Two other biological models were used as well. The NPZD model used by Hood consisted of a detrital compartment (D) added to the Flierl and Davis (1993) NPZ model (see section 3.1.7).

The biological model used by Doney/Glover was similar and was a nitrogen based flow model adapted from Fasham's model of the mixed layer (Fasham et al., 1993). The model is quite flexible in that the flow pathways and model parameters are specified as part of an input file at run time. Currently, the model is formulated as NPZD model and includes both turbulent transport and sinking of the biological components. Coupling between the biological model and the physical model via the absorption coefficient for solar radiation can also be included.

The general equation for any biological scalar at a particular grid level is:

$$\frac{dX}{dt} = -\frac{d\overline{w'X'}}{dz} - \frac{dw_{\mathrm{sinking}}X}{dz} + \text{biology}$$

where $\overline{w'X'}$ is the turbulent flux of X and w_{sinking} is the sinking velocity of species X.

The biological production and consumption terms for the NPZD model are:

$$\frac{dP}{dt} = V_m(I)\frac{PN}{k_s + N} - R_m(1 - e^{-\lambda})Z - \epsilon P$$

$$\frac{dZ}{dt} = \gamma R_m(1 - e^{-\lambda})Z - gZ$$

$$\frac{dN}{dt} = -V_m(I)\frac{PN}{k_s + N} + mD \tag{2}$$

$$\frac{dD}{dt} = (1 - \gamma)R_m(1 - e^{-\lambda})Z + \epsilon P - mD + gZ$$

where parameter values are given in Table II.

Table II. Parameter values used in the Doney and Glover NPZD model.

Parameter	Value	Description
I	—	irradiance
V_m	2.0	maximum phytoplankton growth rate
k_s	0.1	nutrient half saturation coefficent
R_m	1.0	maximum zooplankton growth rate
λ	0.3	Ivlev coefficent
ϵ	0.1	phytoplankton mortality
γ	0.7	egestion fraction
g	0.2	zooplankton mortality
m	1.0	detrital remineralization rate

3.1.4 *Tasks attempted and completed*

- The group explored and compared the behavior of the CONV, PWP and MY mixed layer models. They compared the shape of the vertical temperature profile, the annual cycles of surface temperature and mixed layer depth, conservation of heat and the vertical diffusion characteristics.
- The NPZD models were coupled first with CONV and parameters were adjusted to find 'stable' behavior, i.e. behavior that did not include inherently biological limit cycles, but rather annual cycles controlled by a combination of the annual cycles in solar radiation and mixed layer behavior.
- For the 'stable' parameter sets, the NPZ model was coupled to MY and the behavior compared with that of the coupled CONV - NPZ model.

- Similar runs were conducted with the NPZ model coupled to the PWP model
- The NCAR model was implemented with an NPZD model and tested with several multiyear simulations to demonstrate the influence of the detritus loop.
- An NPZD model was coupled to the CONV model and parameter space explored. A modified NPZD model was coupled with the Hood/Olson version of PWP.

3.1.5 *Results of the comparison of mixed layer models*

The PWP and CONV models behave very similarly, in terms of the annual cycle of sea surface temperature, mixed layer depth, and temperature profile.

Initially, the MY model did not conserve heat, but rather it added significant heat beyond the net heat input across the air-sea boundary, which was evident in both the annual SST cycle and the vertical profiles departing from those of CONV and PWP. (Figs. 1 and 2).

MY includes a bottom boundary layer and a background constant diffusion, initially set at 1.34 x 10^{-5} m^2 s^{-1}. Over an annual cycle a large amount of heat was diffused from the mixed layer into the layer below, especially the bottom well-mixed layer. The extent of this diffusion is shown in a 2-year run where the surface heat exchanges were turned off (Fig. 3). The background diffusion dominated the modelled diffusion resulting from the level-2 closure as shown in Fig. 4, which is a plot of the $K_T(z)$ profile on a $\log_{10}$ plot after 200, 360 and 850 modelled days (day 1 = 120).

The non-conservation of heat was traced to a function that was applied each timestep to keep the odd and even time leapfrog solutions from diverging from each other. G. Flierl replaced the scheme with a 1/2 timestep Euler solution every 100 timesteps, i.e. twice a day. The annual cycles of SST in CONV and MY then were almost identical (Fig. 5), where the background diffusion and the bottom boundary layer in MY were both turned off.

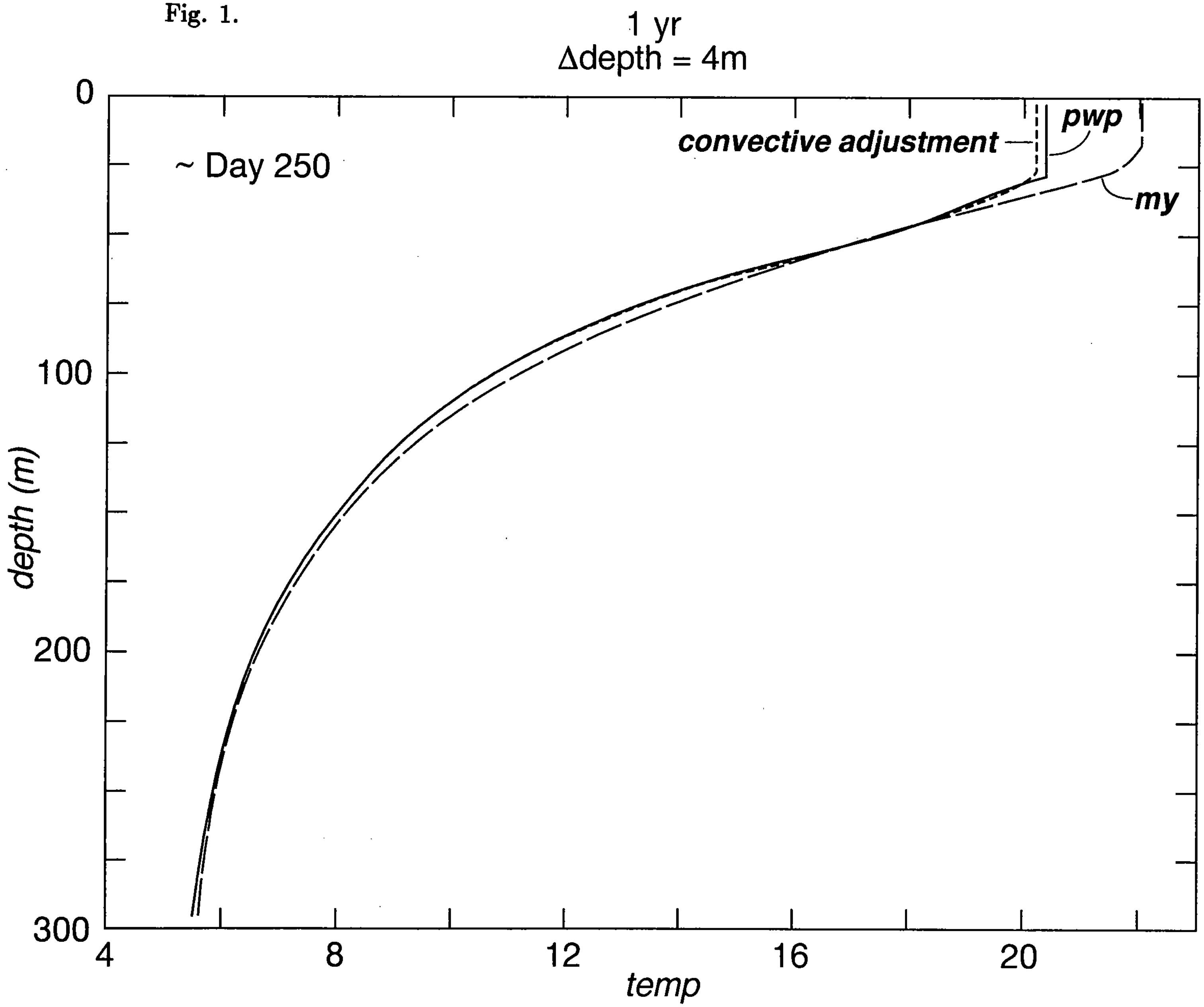
Another feature of MY is that convective mixing due to heat loss at the sea surface takes several timesteps to reach full adjustment for a deep mixed layer, unlike PWP (and CONV) where complete mixing occurs each time step. This behavior will generate propagating waves when PWP is embedded in a circulation model and adjacent gridpoints mix suddenly to different depths. However, the MY model appeared to take close to 10 times the computer time of PWP, so it may not be practical for inclusion in large high resolution 3D circulation models.

The NCAR mixed layer model, based on a fitted similarity solution for the vertical profiles of K_T, is an attractive option. Its ability to simulate a stable annual cycle in the mixed layer is shown in Fig. 6.

As part of the workshop, the NCAR model was transferred to and adapted to run on the NASA EOS interdisciplinary team SCF SGI at WHOI. Using a set of simple, harmonic forcing functions, we generated a physical model solution for a Sargasso Sea like case (Fig. 6a and b). The model produced deep, convective mixing during winter and a shallow mixed layer and seasonal thermocline of approximately the correct amplitude during the summer. A distinct and stable seasonal cycle developed after one year. Notably, the model retains a thick layer of mode water at about eighteen degrees.

3.1.6 *Results with coupled NPZD and mixed layer models*

Fig. 1.



1 yr
Δdepth = 4m
~ Day 250
convective adjustment
pwp
my
depth (m)
temp
0
100
200
300
4
8
12
16
20

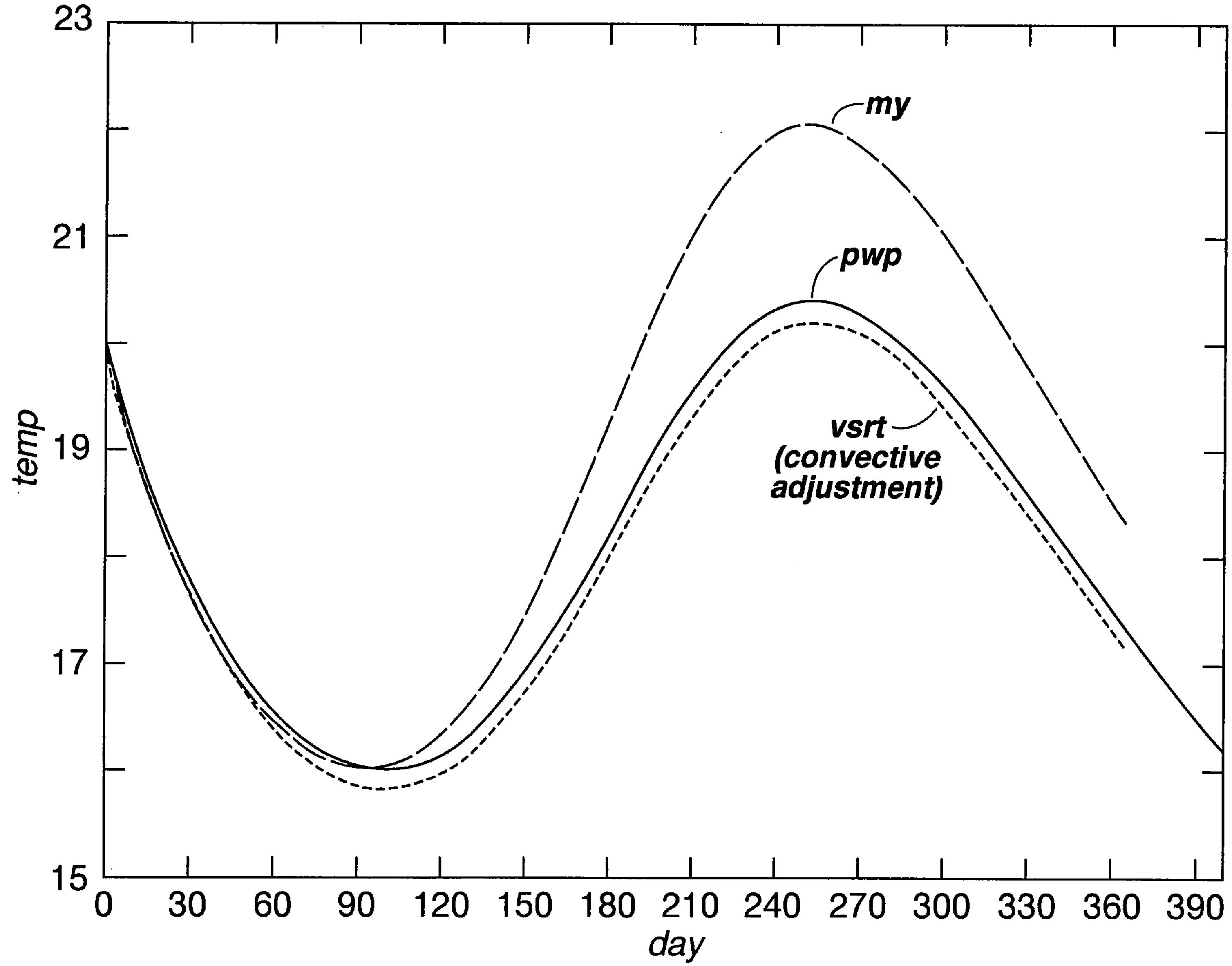
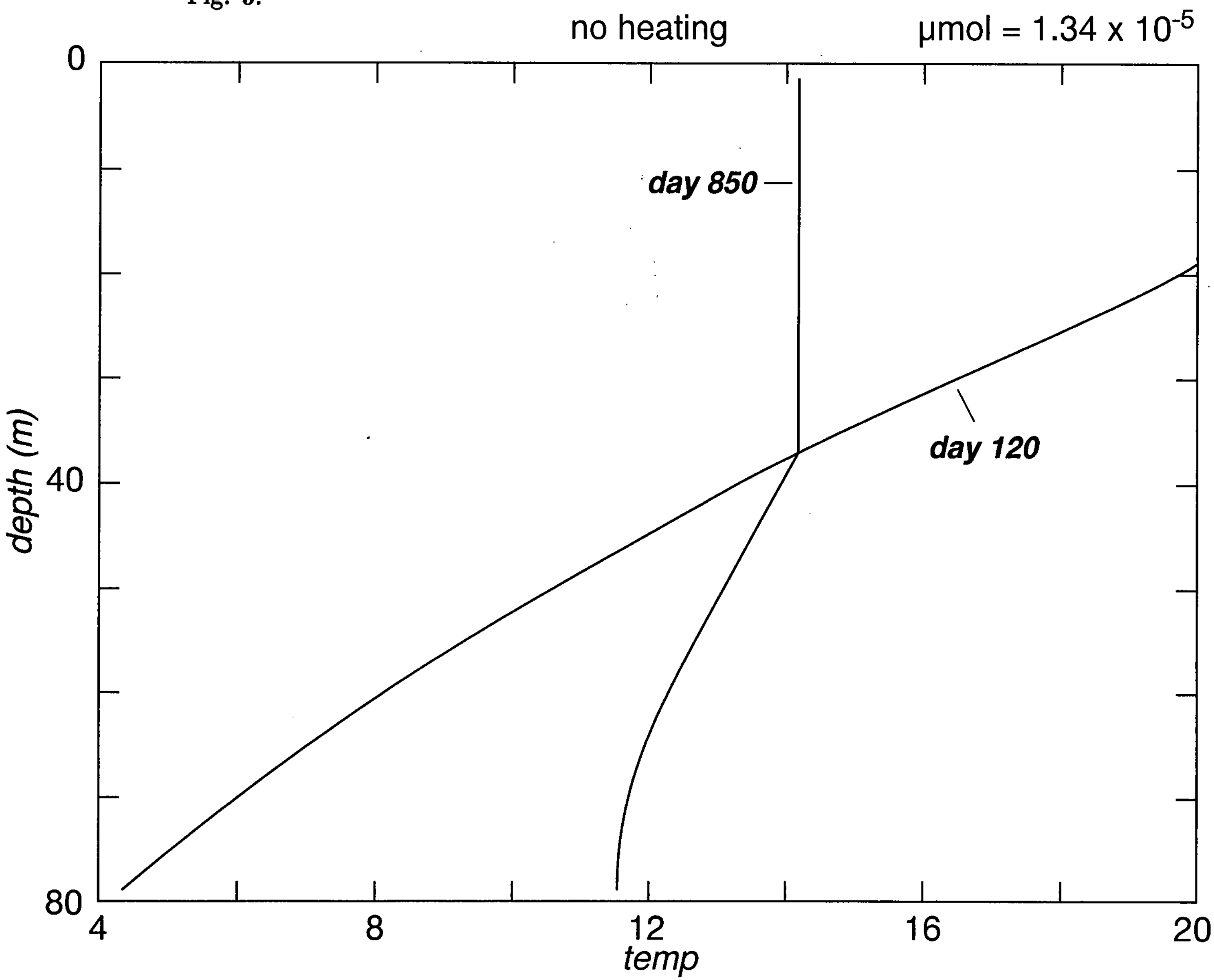

23
21
19
17
15
temp
0
30
60
90
120
150
180
210
240
270
300
330
360
390
day
my
pwp
vsrt
(convective
adjustment)

Fig. 2.

Fig. 3.


no heating
μmol = 1.34 x 10-5
day 850
day 120
depth (m)
temp
0
40
80
4
8
12
16
20

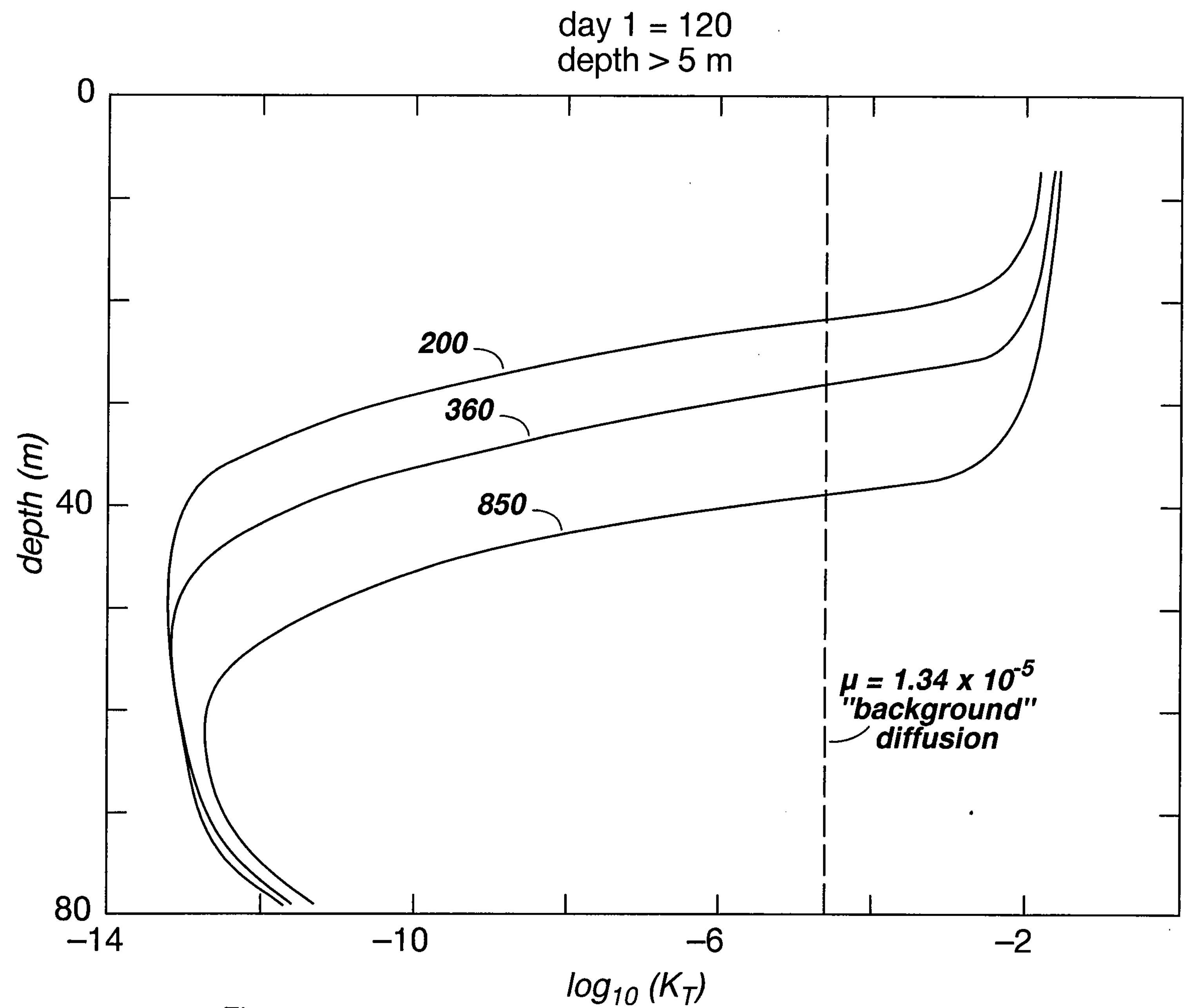

day 1 = 120
depth > 5 m
0
40
80
depth (m)
–14
–10
–6
–2
log10 (KT)
200
360
850
μ = 1.34 x 10-5
"background"
diffusion

Fig. 4.

Fig. 5.