B - MODELING THE GLOBAL OCEANIC CIRCULATION FOR CLIMATIC SPACE AND TIME SCALES

by Klaus HASSELMANN

The relationship between theoretical concepts of large-scale ocean circulation and the only presently existing global ocean circulation model based upon primitive equations shows several mismatches. Global primitive equation models (1) have global dynamics, uniformly applied ;(2) have uniform resolution in space and time (99% of bits are used to describe 1% of the dynamical information) ; and (3) are too expensive for systematic exploration of space-time climatic variability. Theoretical concepts suggest (1) the applicability of "regional" dynamics (surface layers, boundary currents, ACC, equatorial dynamics, bottom water formation, etc.) ; (2) the presence of very different time and space scales in different regions ; and (3) very different ordering of the physics in models.

Regions of the ocean circulation which have been studied in detail with individual models involving quite different physics and space-time scaling are shown in Fig. 1. The purpose of a "taylored global ocean circulation model" is to construct a multi-regional model in which different regions are modelled differently and are coupled together with appropriate matching boundary conditions. Apart from hopefully achieving a more realistic description of the global ocean dynamics and providing a tool for better understanding the physics, it can be estimated that such a model would be about two orders of magnitude faster than a primitive equation model. This would allow the application of these models for "inverse modeling" diagnostic studies in which the model can be tuned systematically on the computer using best-fit algorithms.

Discussion of region I : The Interior Ocean (below the seasonal layer, excluding equatorial regions and western and eastern boundary layers). The only prognostic variables are T, S ; everything else, in particular the entire velocity field, is diagnostic (see figs. 2 and 3). T and S are simply advected, with the advective velocity determined geostrophically. Boundary conditions are straightforward. A number of interesting, still open (and amazingly elementary) questions can be addressed with this model. These include : (1) Can one explain the principle features of density stucture in the interior alone by the advection downwards and horizontally of surface properties (classical "warm water sphere" concept ?) (2) Do all particle trajectories intersect the seasonal layer at some point ? (3) Is friction in the western boundary current really necessary, or does flow develop its own compensating bottom torque to balance the integral wind stress torque ? (4) What happens in regions of closed f/h contours (mid-Atlantic ridge, ACC) ? And last but not least, (5) how do heat flux perturbations at the surface propagate through the interior ocean and affect the heat flux at the surface at later times ?

Closed f/h contours

The barotropic flow may be determined by the generalized Sverdrup relation for variable bottom topography by integrating the mass flow stream function along contours of f/h. The forcing is the curl of the wind stress and the baroclinic bottom torque, which may be expressed by the Jacobian of the depth and the potential energy $\int_0^h \rho\, z dz$. For closed f/h contours the integral of this forcing over the closed f/h circuit must vanish for a stationary solution - a condition which will normally not be satisfied for an arbitrary initial density distribution and wind forcing. A stationary solution can be achieved if friction is invoked, but this requires Gulf Stream order of magnitude barotropic shear flows to balance the integrated torque, an unlikely situation for the mid-Atlantic ridge, for example (although a possibility for the ACC).

The physical problem becomes clearer, however, if one goes back to the non-stationary case. One finds then that if the wind stress and baroclinic bottom torque are regarded as constant, the integrated torque simply spins up a free gyre, with flow parallel to the f/h contours, the gyre velocity growing linearly in time. If, however, the advection of the density structure by the gyre itself is taken into account, this modifies the baroclinic bottom torque, and an oscillation is generated. In the presence of a weak frictional damping, the oscillation gradually decays and approaches an asymptotic steady state in which the net wind stress torque is exactly balanced by the adjusted baroclinic bottom torque. Numerical calculations with primitive equations support the closed f/h gyre oscillation (Figs. 4 and 5). (Comment by P. Welander : This is a very interesting example of the ocean adjusting itself such that the net wind stress torque in a gyre is exactly balanced by the baroclinic bottom torque. It would be interesting to apply the same type of analysis to basin-size wind generated gyres, including the western boundary currents. It may be surmised also here that the gyres achieve the same balance, and and that friction is not required to explain steady state barotropic gyres.)

Region II - Seasonal layer models : On time scales greater than about two weeks, the temperature structure of the seasonal layer can be well represented by a homogeneous layer (depth h) plus an exponential decay below (e-folding depth d) (fig. 6) (errors less than 5%). It is a straightforward matter to invent a generalized Kraus-Turner type model with prognostic variables h, d, T, S (fig. 7) which reproduces quite well the observed seasonal cycle (fig. 8). It is argued that this provides a perfectly adequate and efficient description of the coupling between the interior ocean and atmosphere for climatic time scales.

Region III - Western boundary currents : A similar parametrical approach can be taken to model the gross dynamics of the Gulf Stream-in analogy to similar integral-constraint projections of classical turbulent boundary layer theory (mass, momentum, and energy integral equations). The principal features of the mean Gulf Stream (for example, its position and crossing angle over the f/h contours, dependent on its thermal structure) and its time response to variable forcing by the interior flow can be studied by this technique (fig. 9). A density-driven recirculation regime should be predictable by this model. However, the proper treatment of the prescribed matching boundary conditions coupling the Gulf Stream to the interior solution is still an open question in a parametrical treatment of western boundary currents.

Regions IV, V, VI - Other regions : Equatorial regions, polar fronts, the ACC, etc. must also be included in the global multi-regional model, but this work is still in progress.

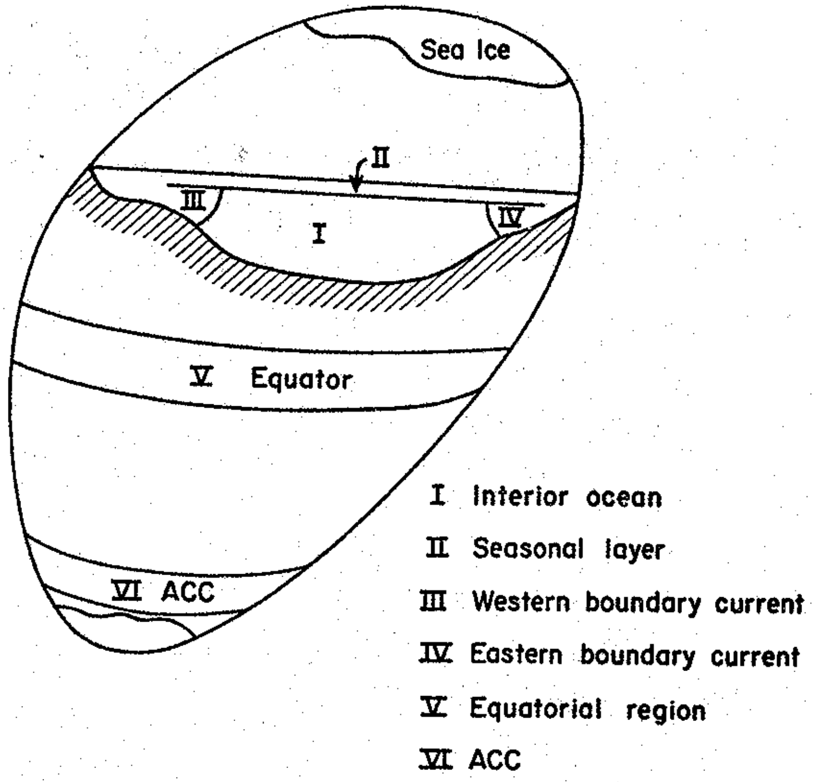

Sea Ice
II
III
I
IV
V Equator
VI ACC
I Interior ocean
II Seasonal layer
III Western boundary current
IV Eastern boundary current
V Equatorial region
VI ACC

FIG. 1

Interior region

primitive equations

$$\varphi \equiv \begin{pmatrix} \underline{u} \\ S \\ T \\ \xi \end{pmatrix} \begin{matrix} \text{(horizontal vel.)} \\ \equiv \underline{\text{State vector}} \\ \\ \\ \end{matrix} \qquad \boxed{\frac{\partial}{\partial t}\varphi = O(\varphi)}$$

Climate ocean circulation model (Pierre Welander)

$T \gtrsim$ 1 month

$L \gtrsim$ 500 km

$$\varphi \equiv \binom{S}{T} \qquad \boxed{\frac{\partial}{\partial t}\binom{S}{T} + \underline{u}\,\nabla\binom{S}{T} + w\frac{\partial}{\partial z}\binom{S}{T} = \begin{pmatrix} Q_S \\ Q_T \end{pmatrix}}$$

Reduction

$$\begin{pmatrix} \underline{u} \\ S \\ T \\ \xi \end{pmatrix} = \begin{pmatrix} \hat{\underline{u}} \\ \xi \end{pmatrix} + \begin{pmatrix} \underline{u}' \\ S \\ T \end{pmatrix}$$

diagnostic because $L \gg R_0$

baroclinic

barotropic

diagnostic
because fast

(Global 5° model, 5 layers,
integrates 1000 yrs in O (1hr)
Cray time)

FIG. 2

Climate ocean circulation model (Pierre Welander)

$T \gtrsim 1$ month

$L \gtrsim 500$ km

$\varphi \equiv \binom{S}{T}$

$$\boxed{\frac{\partial}{\partial t}\binom{S}{T} + \underline{u}\nabla\binom{S}{T} + w\frac{\partial}{\partial z}\binom{S}{T} = \begin{vmatrix} Q_S \\ Q_T \end{vmatrix}}$$

Boundary conditions :

(1) $\binom{S}{T}$ Prescribed on inflow boundaries

(2) w at top

(3) zero barotropic normal flow at "eastern" boundary of f/h contours

FIG. 3

RESONANT BAROTROPIC VORTICITY GYRE

① Vorticity Balance For Closed $\frac{f}{h}$-Contours

No Sverdrup balance possible, but:

$$\partial_t \underline{\nabla}\left(\frac{1}{h}\underline{\nabla}\overline{\psi}\right) = \mathrm{rot}\left(\frac{\tau}{h}\right) - \mathrm{rot}\left(\frac{1}{h}\int_{-h}^{0} dz\, \underline{\nabla}p'\right)$$

$$\Downarrow$$

Strong (resonant) response: $U = O\left(\frac{\tau T}{H}\right) \approx 10^{-4}\frac{m}{s}$

Mass transport lags baroclinic pressure by $\frac{T}{4}$

② Feedback Of The Resonant Gyre

Resonant velocity ⇒ Density field ⇒ Depth averaged pressure ⇒ Resonant velocity

Model:

$$\left.\begin{array}{l}\text{Resonant vorticity equation}\\ \text{Linearised density equation}\end{array}\right\}\text{Oscillation on each contour with period } T \sim \frac{f}{\beta N h}\ (*)$$

③ Comparison With A Numerical Model

5-layer primitive equation model of E. Maier-Reimer: a) Parameter test of (*) (Fig 1)

b) Initialisation of a resonant gyre (Fig 2) c) Oscillation of masstransport (Fig 3)

④ Application

Circumpolar current, Mid-Atlantic ridge

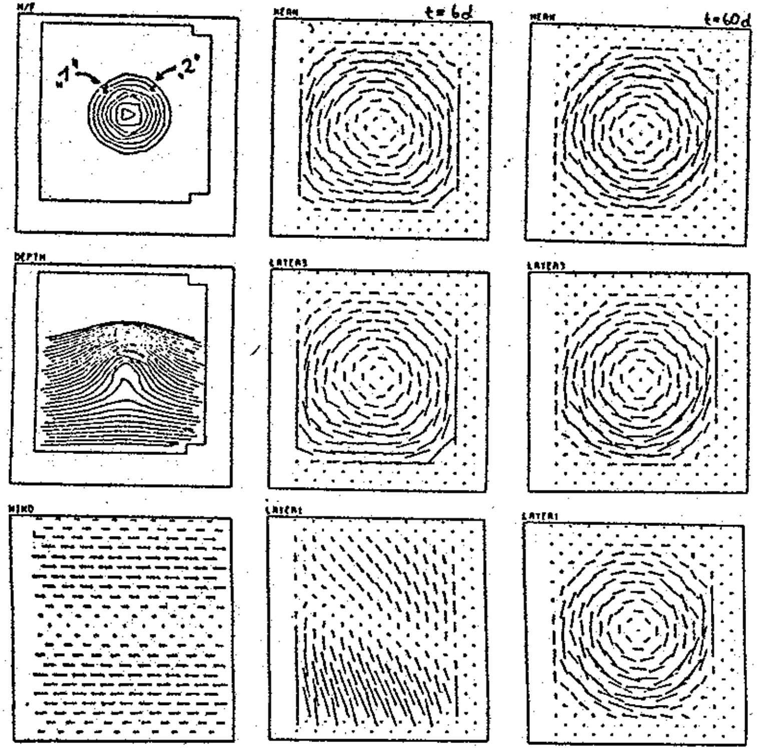
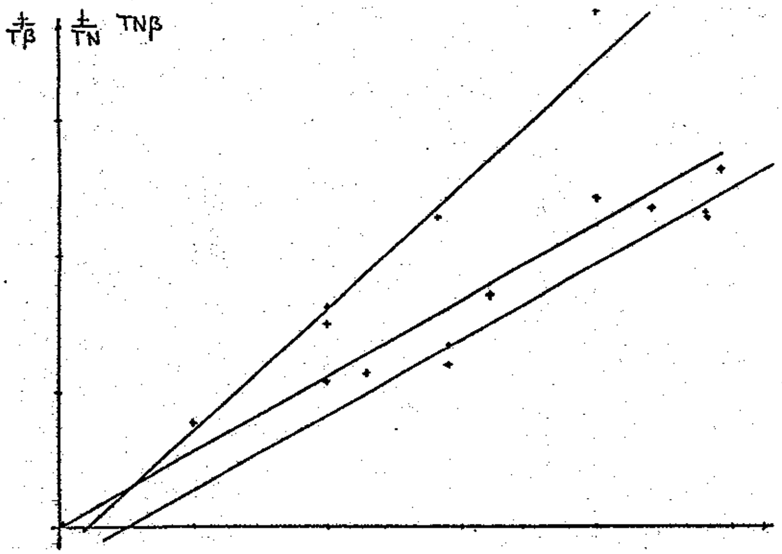


FIG. 4



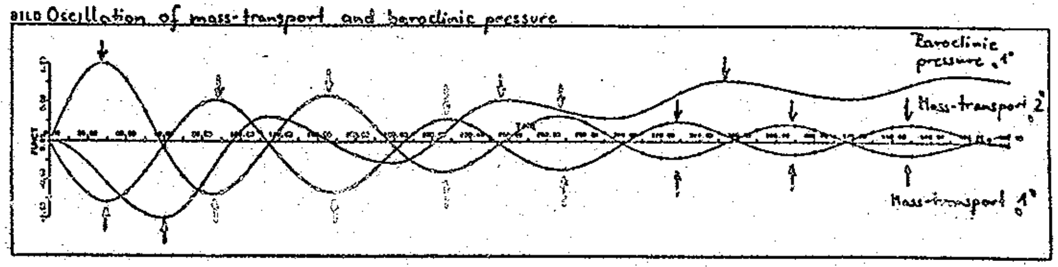


FIG. 5

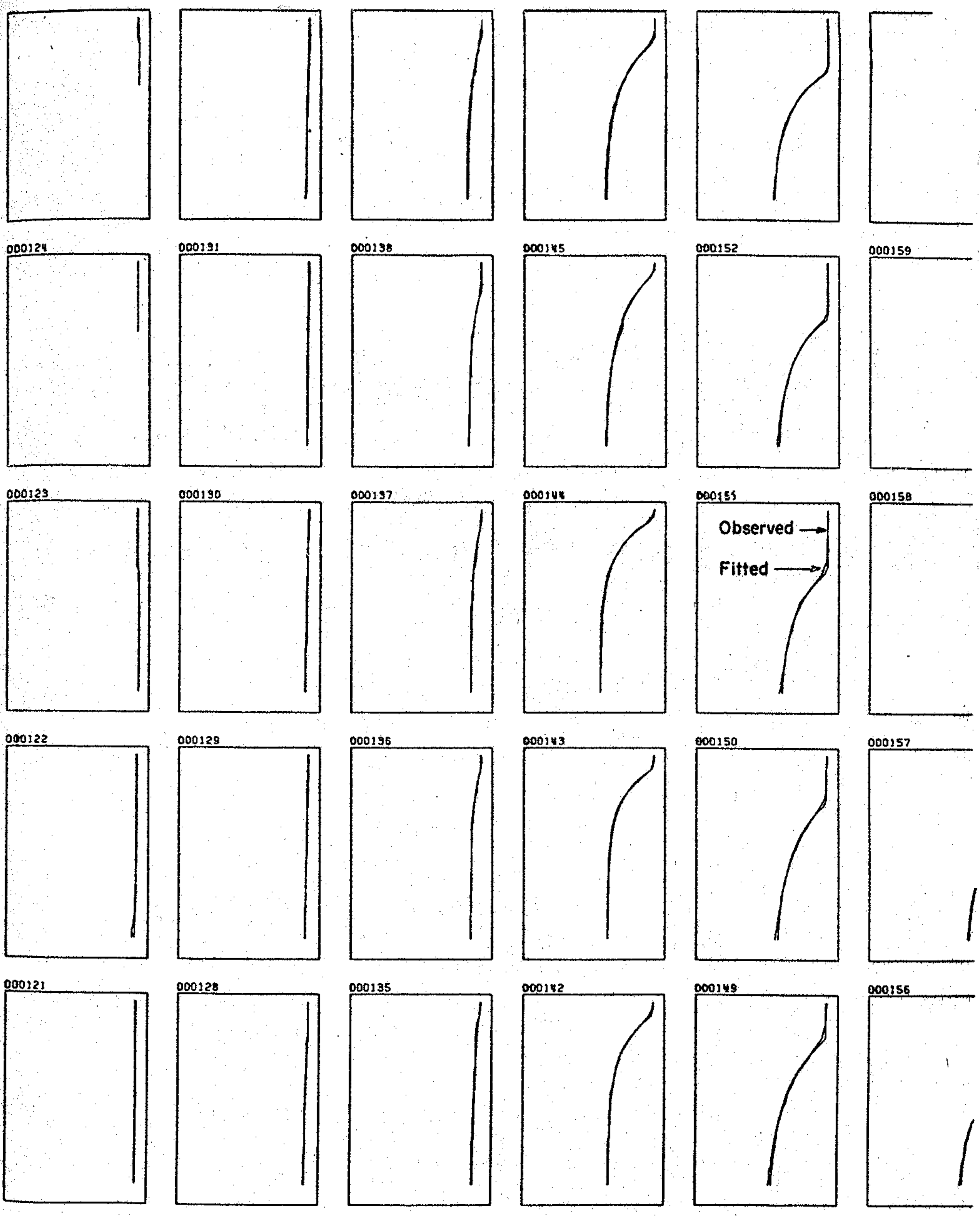


FIG. 6 WEATHER SHIPS DATA (SAME DEGREE OF FIT APPLIES FOR ALL SHIPS ANALYSED)

DETLEV MÜLLER

Id - upper layer model

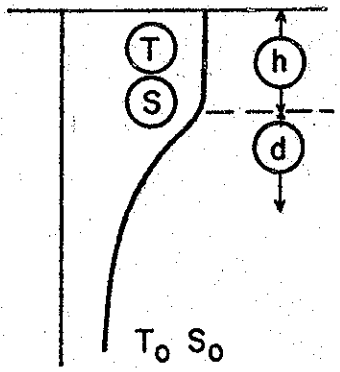
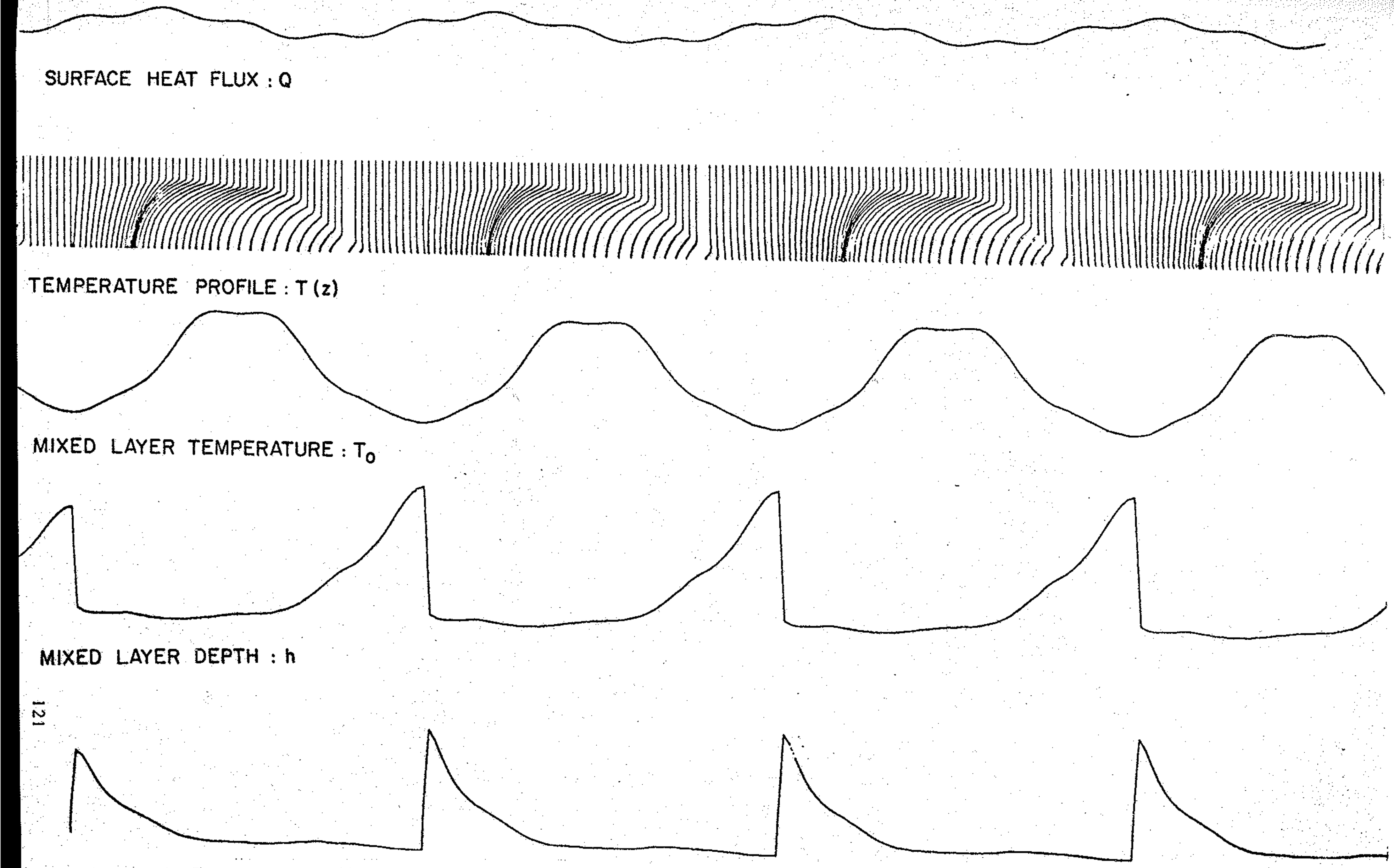


FIG. 7

MODEL RESULTS



SURFACE HEAT FLUX : Q

TEMPERATURE PROFILE : T (z)

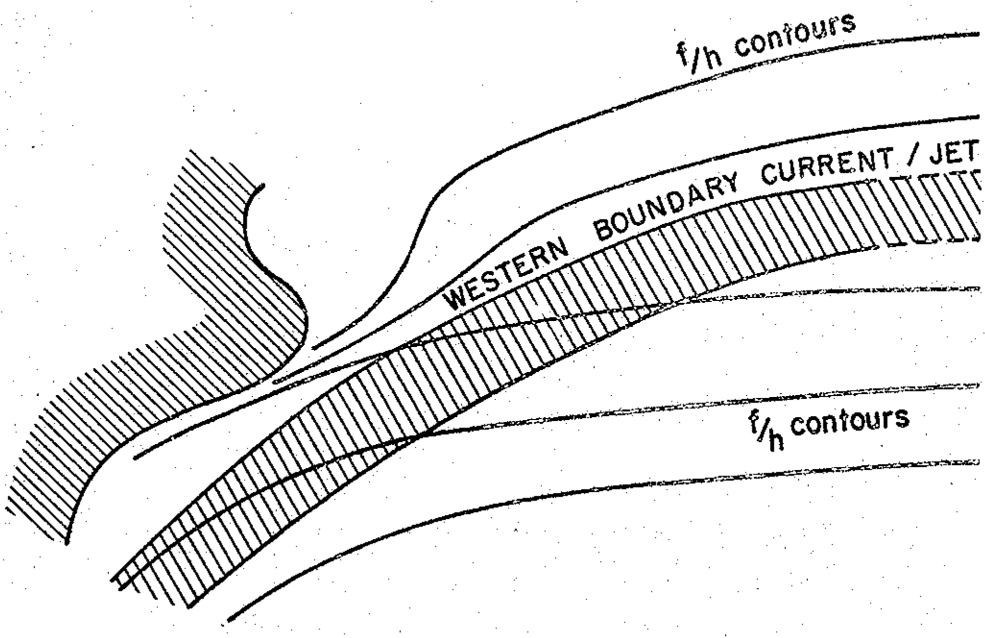
MIXED LAYER TEMPERATURE : T_0

MIXED LAYER DEPTH : h

SEASONAL THERMOCLINE e-FOLDING DEPTH : D

FIG. 8

WESTERN BOUNDARY CURRENT (REGION III)



BOUNDARY CONDITIONS

(1) $\rho\,(z)$ prescribed on all inflow surfaces

(2) $\hat{u}_n = u'_n = 0$ on north side at wall

(3) $\hat{u}_n$ prescribed on south side by interior flow

JET must follow $f/_h$ contour when $\underline{\nabla}\,\underline{\tau}$ becomes zero
(WARREN , ROBINSON)

FIG. 9