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A METHOD FOR DIAGNOSING CLIMATE CHANGE AND OCEAN VENTILATION USING HYDROGRAPHIC DATA

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ABSTRACT

Climate change that is produced by the Greenhouse Effect, for example, can affect the sub-surface water column by three different mechanisms. First, the water from the mixed layer that is subducted into the ocean interior can be warmed, second, the subducted water can be freshened through changes in evaporation and precipitation, and third, the rates of renewal of water masses can change so that parts of the water column are displaced vertically. A new method for diagnosing the sub-surface temporal changes in hydrography data is described in terms of these three processes: "pure warming", "pure freshening", and "pure heave".

THE THREE SUBDUCTION PROCESSES

Pure Warming

Under a Greenhouse warming scenario, the most obvious change to water in the ocean mixed layer is that it becomes warmer. This simple warming (at constant salinity) changes the density of fluid parcels and these changes of density are responsible for the increased sea level (i.e. thermal expansion). The physical processes that cause subduction of fluid from the mixed layer into the thermocline are assumed to continue much as before global warming, and so this simplest of scenarios leads to the pumping of warmed fluid parcels into the thermocline where they mix with the existing fluid of the same density. This process of "pure warming subduction" was used by Church, Godfrey, Jackett and McDougall (1991) in a model of the sea level rise caused by ocean thermal expansion, and here we elaborate a little on the justification for this physical model.

Consider the warming of parcel 1 in Figure 1(a) without changing the salinity of this parcel. The fluid properties are then given by point 2 in Figure 1(b). When this parcel is subducted it will join the thermocline at its own density and so will mix with thermocline water of properties (S_3, θ_3), forming a mixture with properties (S_4, θ_4). Now consider the fluid that is shaded in Figure 1(a), containing all the fluid of original properties (S_1, θ_1) and (S_3, θ_3). The average properties of this fluid was at (S_5, θ_5) and after the warming and the subduction of fluid in the upper layer, the average properties of all this marked fluid is the mixture of (S_1, θ_1) and (S_4, θ_4), namely (S_6, θ_6). The important point to note is that the average salinity of the marked fluid has not changed and so $S_5 = S_6$. Also, because there is no change in the ocean beneath the shaded fluid of Figure 1(a), the average depth of these fluid parcels has not changed so that $z_5 = z_6$, and we shall use this fact in the next section. Parcel 7 is marked on figure 1b to indicate that when analyzing data on a density horizon (e.g. a neutral surface, McDougall, [1987]) this subduction process is equivalent to a cooling and freshening in the density horizon. From hydrographic data, it is often easier to measure the difference between cruises on the density horizon $[(S_7, \theta_7) - (S_6, \theta_6)]$ than it is at constant depth.

Pure Freshening

While the primary response of the mixed layer (S, θ) properties to Greenhouse-induced climate change may be a warming, nevertheless changes are expected in the patterns of net evaporation (E) and precipitation (P), and this will lead to a change of the sea surface salinity. Following Manabe, Bryan and Spelman (1990) we have reason to expect that in the latitudes where subduction of thermocline water occurs in

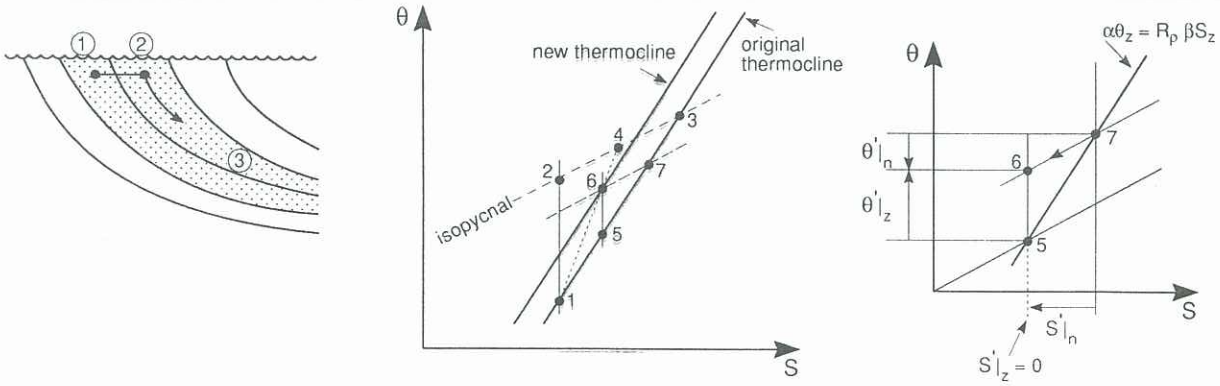

Figure 1 The warming process. (a) Parcel 1 is warmed at constant salinity so that it attains the properties of point 2 which is the same density as parcel 3. (b) Upon subduction of parcel 2, it mixes with the thermocline fluid, 3, at that "density", producing a parcel, 4, of intermediate properties. The average properties of all the shaded fluid of Figure (a) is at point 5 in Figure (b), and moves to point 6 under this purely warming subduction scenario. Note that $S_6 = S_5$ and that parcel 7 of the old thermocline has the same density as the cooler and fresher parcel 6 of the new thermocline. Figure (c) shows an enlargement of part of Figure (b).

the Southern Ocean, the sea-surface salinity is expected to be less than before Greenhouse warming.

Here we take the extreme example of a freshening of the mixed layer while, at the same time, the temperature of the mixed-layer fluid is unchanged. One may expect more realistically that the mixed layer fluid will be both warmed and freshened under Greenhouse warming.

The numbers of the fluid parcels in the "pure freshening" scenario of Figure 2 follow closely those of the previous section. Suffice to say that the net observable result of the sequence of freshening, subduction and mixing is that an average fluid parcel 5 on the original thermocline is freshened at constant potential temperature to point 6 on the new thermocline S,θ curve. The figure also shows the contrast $(S_6 - S_7, \theta_6 - \theta_7)$ in properties along a neutral surface between the two epochs.

Pure Heaving

The special cases of the previous two subsections have tacitly assumed that the rates of suction and pumping of fluid into and out of each pair of layers does not change. Now we allow for variations in the rate of renewal of water masses between pairs of neutral surfaces. Such changes may occur through changes in the patterns of wind stress curl for example. Figure 3(a) shows what is in mind here. A fluid parcel is extracted from a layer and is subducted into another. The temperature and salinity of the parcel is fortuitously adjusted to match that of the layer into which it is subducted. Of course, in practice the parcels' temperature and salinity would not be expected to exactly match that of the original thermocline at that density, and a linear combination of the previous processes would also need to be invoked.

While there is no signature of this process on the S,θ diagram, the process does affect observations at fixed depths. The marked fluid on Figure 3 has moved vertically downwards as a result of this mechanism and so at a fixed depth the density is observed to decrease in this depth range.

The sense (sign) of this process is less certain than that of the pure warming or pure freshening processes above. It has been drawn in figure 3 in the sense consistent with global warming in that at each depth the fluid becomes less dense and so gives a rise in sea-level, consistent with the fact that the fluid parcel that is subducted high in the water column in Figure 3a is much warmer than it was at depth.

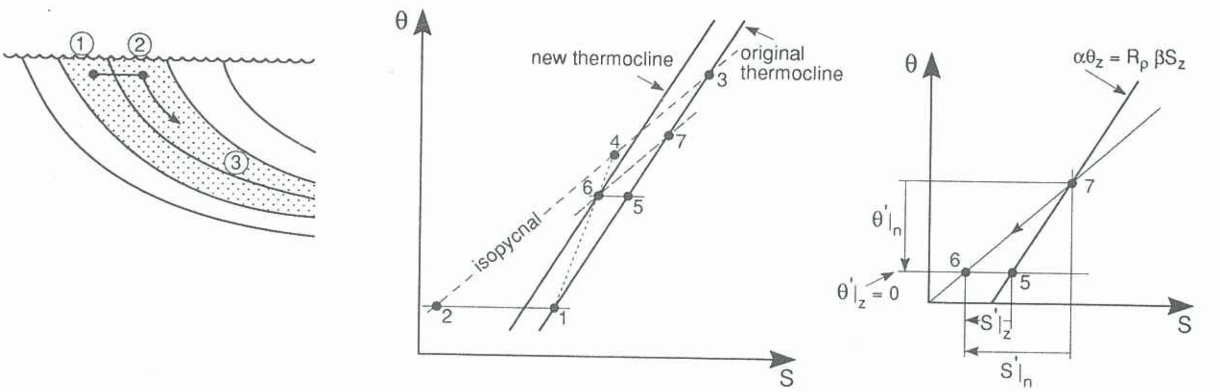

Figure 2 The freshening process. (a) A parcel, 1, from the lower shaded layer is made fresher while holding its temperature constant. The resulting parcel, 2, is then subducted and mixed with thermocline fluid of properties (S_3, θ_3), giving a mixture, parcel 4. The average properties of all the marked fluid (see the shading in Figure a) changes from (S_5, θ_5) to (S_6, θ_6). Note that $\theta_6 = \theta_5$ and that parcel 7 from the original thermocline has the same density as the cooler and fresher fluid of parcel 6 of the new thermocline. Figure (c) shows an enlargement of part of Figure (b).

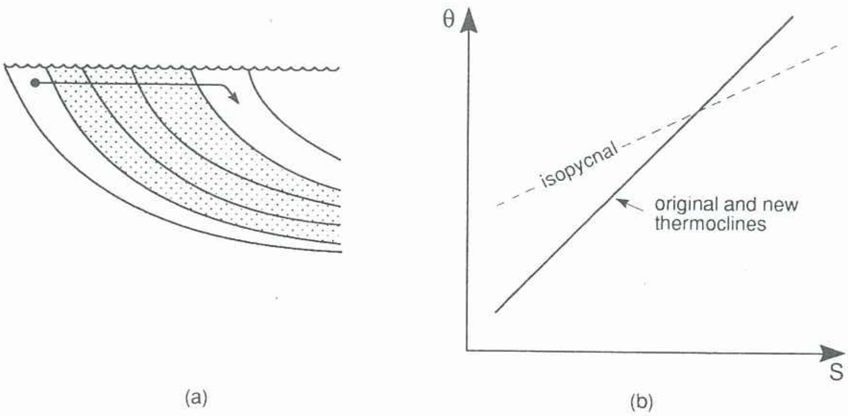

Figure 3 Pure heaving process. These figures illustrate the third subduction process where the rates of pumping into and out of various layers change, but the fluid properties of water being subducted along each isopycnal are identical to their pre-Greenhouse values. This is evident in Figure (b) where no change in water-mass properties (i.e. change in properties at constant density) is observed. In the shaded region of Figure (a), the water column shifts downward and so at fixed depth, z, the fluid density is decreased, and so the sea level rises due to this process.

COMPARISON OF DATA AT CONSTANT DEPTH AND ALONG NEUTRAL SURFACES

In addition to the signatures of the three different subduction processes on the observed change of S and θ along neutral surfaces, each process also has a signature in the changes of S and θ at constant depth. For example, in the "pure warming" process (Figure 1(b)) nether the parcel's depth nor its salinity change (i.e. $z_6 = z_5$ and $S_6 = S_5$) while its potential temperature increases by $\theta_5 - \theta_6$. While there is no net vertical motion of fluid parcels in both the "pure warming" and "pure freshening" processes, neutral surfaces do move vertically. In this section we will establish the relationships between the observed changes of S and θ, both along neutral surfaces and at constant depth, for each of the three subduction process that we are considering.

Consider two vertical CTD casts taken at the same latitude and longitude, but separated in time (see Figure 4). The change in a scalar quantity, ψ, at fixed depth is given by $\psi'|_z = \psi_c - \psi_a$, while that along the neutral surface is $\psi'|_n = \psi_b - \psi_a$. The difference between $\psi'|_z$ and $\psi'|_n$ is equal to $-(\psi_b - \psi_c)$ and this can also be expressed in terms of the change in height of the neutral surface, $\mathcal{N}'$, times the vertical gradient of ψ, ψ_z (assuming that the vertical motions are small enough so that $\psi_b - \psi_c$ can be approximated by the first term in a vertical Taylor expansion of ψ, $\mathcal{N}'\psi_z$.) Writing this result for potential temperature and salinity, we have

$$\theta'|_z = \theta'|_n - \mathcal{N}'\theta_z \quad \text{and} \quad S'|_z = S'|_n - \mathcal{N}'S_z. \tag{1}$$

It is more useful to express these equations in density units by multiplying them by the thermal expansion and haline contraction coefficients, α and β, respectively, where

$$\alpha \equiv -\frac{1}{\rho}\frac{\partial \rho}{\partial \theta}\bigg|_{S,p} \quad \text{and} \quad \beta \equiv \frac{1}{\rho}\frac{\partial \rho}{\partial S}\bigg|_{\theta,p} \tag{2}$$

giving

$$\alpha\theta'|_z = \alpha\theta'|_n - \mathcal{N}'\alpha\theta_z \quad \text{and} \quad \beta S'|_z = \beta S'|_n - \mathcal{N}'\beta S_z. \tag{3}$$

Along a neutral surface we know that (McDougall, 1987)

$$\alpha\theta'|_n = \beta S'|_n, \tag{4}$$

while at any height the vertical gradients, θ_z and S_z are known, so that $\alpha\theta_z$ and βS_z are related through the stability ratio, R_ρ, defined by

$$\alpha\theta_z = R_\rho\, \beta S_z. \tag{5}$$

To deduce the relationships between the observed variables $S'|_z$, $\theta'|_z$, $S'|_n$, $\theta'|_n$ and $\mathcal{N}'$ for each of the three subduction processes, we examine the geometry of Figures 1(c) and 2(c).

For the pure warming process of Figure 1(c) the change in potential temperature from point 5 to point 6 happens at fixed depth, so that $\theta'|_z = \theta_6 - \theta_5$. It can be seen from the geometry of Figure 1(c) that

$$\begin{aligned}(\alpha\theta'|_z - \alpha\theta'|_n) &= \alpha(\theta_7 - \theta_5) = R_\rho\,\beta(S_7 - S_5) \\ &= R_\rho\,\beta(S_7 - S_6) = -R_\rho\,\beta S'|_n.\end{aligned} \tag{6}$$

Hence we have

$$\beta S'|_z = 0, \quad \beta S'|_n = \mathcal{N}'\beta S_z, \quad \frac{\alpha\theta'|_n}{\alpha\theta'|_z} = -(R_\rho - 1)^{-1} \tag{7}$$

for pure warming.

Similarly, for the pure freshening subduction process, from Figure 2(c) we find that $-\alpha\theta'|_n = -R_\rho\,\beta(S'|_n - S'|_z)$ so that

$$\alpha\theta'|_z = 0, \quad \alpha\theta'|_n = \mathcal{N}'\alpha\theta_z, \quad \frac{\beta S'|_n}{\beta S'|_z} = (1 - R_\rho^{-1})^{-1} \tag{8}$$

for pure freshening.

The third subduction process is equivalent to vertical heaving of the water column with no changes for S or θ along neutral surfaces, so that

$$\alpha\theta'|_n = \beta S'|_n = 0, \quad \beta S'|_z = -\mathcal{N}'\beta S_z, \quad \alpha\theta'|_z = -\mathcal{N}'\alpha\theta_z \tag{9}$$

for pure heaving. These three relationships, (7) - (9), can be used to draw vectors of each subduction process on diagrams whose axes are chosen from among the observed variables $S'|_z$, $\theta'|_z$, $S'|_n$, $\theta'|_n$ and $\mathcal{N}'$. It makes sense to deal in the six dimensionless variables that appear in (3), namely $\alpha\theta'|_z$, $\alpha\theta'|_n$, $\mathcal{N}'\alpha\theta_z$, $\beta S'|_z$, $\beta S'|_n$ and $\mathcal{N}'\beta S_z$. The fact that the two equations in (3) are satisfied immediately reduces the number of independent variables from six to four, and the definitions (4) and (5) of the neutral surface and of the stability ratio further reduces the number of independent variables to two. This means that while there are many pairs of parameters to choose as the axes for a plot, any pair should contain the same information, (except for the two degenerate pairs (from (4) and (5)), $\alpha\theta'|_n$ and $\beta S'|_n$, $\mathcal{N}'\alpha\theta_z$ and $\mathcal{N}'\beta S_z$, where all the data lie on a line (for a constant R_ρ)).

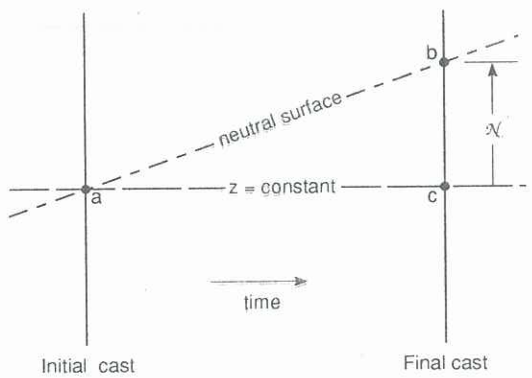

Figure 4 Sketch showing two casts from the same latitude and longitude, but separated in time. Points a and c are at the same depth on both casts, and points a and b lie on the same neutral surface, that is, loosely speaking, they have the same "density". $\mathcal{N}'$ is the change in the height of the neutral surface over this time interval. The change of a scalar quantity, ψ, along the neutral surface is related to the change at constant depth by $\psi'|_z = \psi'|_n - \mathcal{N}'\psi_z$.

EVALUATION OF THE THREE SUBDUCTION MECHANISMS USING AN INVERSE APPROACH

The three ventilation models, as expressed by (7), (8), and (9) give linear relations between the six "observable" quantities $\alpha\theta'|_z$, $\alpha\theta'|_n$, $\mathcal{N}'\alpha\theta_z$, $\beta S'|_z$, $\beta S'|_n$ and $\mathcal{N}'\beta S_z$. Each of these six quantities is due to a linear combination of the three subduction mechanisms, and these relationships are written in matrix form as

$$\frac{\rho^{-1}\rho'|_z}{(R_\rho - 1)}\begin{bmatrix} -(R_\rho - 1) & 0 & -R_\rho \\ 1 & R_\rho & 0 \\ R_\rho & R_\rho & R_\rho \\ 0 & (R_\rho - 1) & -1 \\ 1 & R_\rho & 0 \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} A^w \\ A^f \\ A^b \end{bmatrix} = \begin{bmatrix} \alpha\theta'|_z \\ \alpha\theta'|_n \\ \mathcal{N}'\alpha\theta_z \\ \beta S'|_z \\ \beta S'|_n \\ \mathcal{N}'\beta S_z \end{bmatrix} \quad (10)$$

where the three columns represent the effects of the pure warming, pure freshening and pure heave subduction processes respectively on the six observable quantities, and A^w, A^f and A^h are the proportions of each process. In this system the weighting for each process is such that equal values of A^w, A^f and A^h give equal contribution to sea-level rise, $\rho^{-1}\rho'|_z$. This choice is based on the premise that we have no *a priori* knowledge of the relative strength of the three processes (although we do have prejudices about the sign of each process)

RESULTS

This system of equations has rank 2 and is formally underdetermined. We have found the minimum norm solution from the SVD procedure and have also obtained over-determined solutions by considering only one subduction process at a time to find the amount of the data that is explained by a single process. Both methods indicate that for neutral densities between 26.8 kg m^{-3} and 27.2 kg m^{-3} the pure warming process is dominant, while for the deeper half of Antarctic Intermediate Water both freshening and warming are implicated. (SubAntarctic Mode Water has neutral density less than 27.0 kg m^{-3} and lies between depths of 150 m and 500 m, while Antarctic Intermediate Water has neutral density between 27.0 kg m^{-3} and 27.4 kg m^{-3}))

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