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DISCUSSION FOLLOWING INVITED PAPER

G. de Q. ROBIN: Do you have any comments yourself on this paper?

E.G. JOSBERGER: I slid many of them in while I was reading it, but I do have some general comments. Success or failure [of an iceberg towing project] will depend more on advanced knowledge of oceanographic factors and conditions than on anything else. More detailed knowledge is needed on the direction and speed of eddies and other elements. When we have this more detailed knowledge, we can develop an algorithm and a computer program that would suggest the best routing for a tow.

P.D. KILLWORTH: I would like to stress two aspects of ocean dynamics of direct relevance to towing plans. First, I wish to support Gordon's comments on eddying motions in the circumpolar current. Eddies are found all round the current, with small horizontal scales (50-60 km) and high velocities (30-50 cm sec^{-1}). Although modellers can now simulate such eddies numerically, their prediction remains elusive. Attempts to tow an iceberg through the current is likely to encounter several periods in which the eddy current is not just against the direction of tow, but actually somewhat faster! Although it is reasonable to expect monitoring of such eddies by satellite-carried radar altimeters in the next decade, the degree of randomness in their motion and the low manoeuvrability of a towed iceberg make it unlikely that it will be possible to optimise the towing route.

Second, I would like to discuss effects of convection (large-scale thermal and/or saline-driven vertical motions). It was suggested that if there is sufficient turbulence beneath an iceberg (as might be the case during towing, for example) then melting under a berg could be as important as melting at the side (as discussed by H.E. Huppert later in the meeting). Some confirmation of this was given by the experiments of D.S. Russell-Head in Melbourne. Evidence of the effectiveness of convection (albeit on sea ice, not bergs) for removal of ice is given in D.G. Martinson, P.D. Killworth and A.L. Gordon (submitted to the Journal of Physical Oceanography). If the berg is forced to remain in southern waters for long, a sizeable amount may be lost by convection in addition to the loss due to melting in more northern waters.

ROBIN: If you are towing an iceberg through the Antarctic convergence, the melt rates in the warmer water north of the convergence will be a more important factor than melting in the convergence.

KILLWORTH: Melting in the convergence will be a minor factor, <u>if</u> you ever get out of the convergence!

ROBIN: The effect will be rather small compared to later.

H.E. HUPPERT: The argument in your paper is a little inconsistent. The melt rate is a property of changes in sea-water temperature. Fresh melt water comes out of the berg and produces a stratification and this would make the water under the iceberg more stable, since the stratification tends to inhibit convection. Therefore, the amount of melting is less than you imply.

KILLWORTH: Satellite photographs of the Weddell gyre show, about every other year, a polynya — about one million square kilometers of open ice-free water drifting west. Why does the ice disappear from this area? The only heat source available is by convection of warm deep water from below and we have a model to explain how this might happen. Deep convection could happen if an iceberg were stationary for a matter of weeks.

HUPPERT: The polynya is in sea ice, not fresh-water ice down to 200 to 250 m; this is a dif-

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ferent order of problem altogether.
W.F. WEEKS: Are you suggesting that the Weddell polynya is oceanographically controlled?
KILLWORTH: Yes.
WEEKS: I do not believe it. I do not think that is correct. Meteorological effects drive the ice off and keep new ice from drifting in.
KILLWORTH: I do not believe there are wind divergences there that could do it.
T.E. VINJE: Some calculations by a Russian scientist show that there is a maximum wind divergence area in this region. I therefore think the polynya is caused by a combination of meteorological and oceanographic effects. The high melt rates suggested (0.5 m per day) by warm deep water convection would mean all the ice would be gone from a convection area in about two days, and this seems unrealistic to me.
KILLWORTH: The polynya does in fact appear very rapidly. Ice cover drops by a factor of 10 over a very short time span.
J.F. NYE: I realize the study of Antarctic eddies is only just beginning, but the problem of how you represent their results will arise: how you represent flow. There are two kinds of points where the velocity of flow is momentarily zero: the zero at the centre of an eddy and the zero between two eddies that are rotating in the same sense (e.g. both clockwise). I suggest it may be possible to use the zeros in towing. What would happen if you towed in such a way as to remain in a zero, and let it carry you through the convergence? What is the track of the zeros – more east-west or more north-south? And if you do follow a zero, might it disappear by meeting another zero? Some elementary work needs to be done.
KILLWORTH: Those are very interesting questions but we simply have not enough data. We do not have the technology we need even to define one eddy adequately. When we have access to satellite altimetry, that should show a reasonably good surface signal and give us the topography; now, all we have is surface temperature readings.
R.Q. ROBE: In the Atlantic, where the Labrador current meets the Gulf Stream, icebergs are sometimes found south of the Gulf Stream. They enter a cyclonic meander of the stronger current which then pinches off to become an eddy which carries the berg through the Gulf Stream isolated in a pool of colder water. The icebergs may last a couple of weeks on the warm side of the Gulf Stream. Perhaps if you were towing a berg and could place yourself in the formation area of an eddy, the eddy could carry the iceberg across the circumpolar current.
ROBIN: One ought to investigate the chances of picking up an iceberg for towing on the other side of the circumpolar current. Those are not only icebergs that have made the crossing without outside intervention, but they have also demonstrated the effective structural integrity that, as Dr Weeks pointed out, is a primary requirement.
KILLWORTH: This implies that it might be useful to look for areas of high eddy activity rather than low.
ROBIN: Yes, it does.
KILLWORTH [Shows figure 9 from paper by J R E Lutjeharms and D J Baker Jr "A statistical analysis of the meso-scale dynamics of the Southern Ocean", *Deep-Sea Research* 27(2A) 1980: 145-159.]
This implies that there is a connection between under-sea topography and eddying; perhaps the more topography there is, the more eddies.
G. MOUGIN: Can you specify whether baroclinic eddies are the same as warm-core or cold-core coalescence eddies?
KILLWORTH: We cannot say; there is not enough dynamical evidence at present. We have a theory of small-amplitude eddy formation, but the calculations break down on large-amplitude eddies. And full-scale numerical calculations involve so many factors that it is difficult to spot which ones are causative and which dependent.
HUPPERT: If we can go back to Mr Robe's point for a moment, it seems to me that the circumstances may not apply to the Antarctic. In the Gulf Stream, an eddy or cold ring can get pinched off and carry an iceberg south; alternatively, an eddy of warm water from south of the Gulf Stream could be carried across it to the north. Baroclinic instabilities are very different. It is not clear that one would want to go looking for eddies to carry the tow. In an eddy area there would be lots of large-scale motion and the difficulties of starting a tow would be increased, though the later progress of the tow might be eased. On the other hand, starting the tow in calm water might be easier but lead to more difficulties later. What you lose on the swings you gain on the roundabouts. But finding the iceberg north of the circumpolar current would be best of all.
MOUGIN: When you speak of a correlation between topography and eddy density, are you saying that topography triggers eddies? There is a different type of turbulence from a sea-mount in a current, for example, where eddies surface some hundreds of kilometers down-current. You seem to be showing a correlation between under-sea topography and general eddy density which could have implications for our iceberg tows, some of their route towards Australia following an under-sea channel with Marion and Crozet islands on the north, Ob and Lena Guyot sea-mounts on the south.