UNIVERSITY OF CAMBRIDGE

MATHEMATICAL TRIPOS Part III

Friday, 8 June, 2012 9:00 am to 11:00 am

PAPER 80

THE PHYSICS OF THE POLAR OCEANS, SEA ICE AND CLIMATE CHANGE

*Attempt no more than **THREE** questions.*

*There are **FOUR** questions in total.*

The questions carry equal weight.

In all questions assume that the latent heat of fusion of ice is 336 kJ kg^{-1}, and its specific heat is 2.1 kJ kg^{-1} K^{-1}. The psu, or practical salinity unit, is equivalent to 1 part per thousand.

STATIONERY REQUIREMENTS
Cover sheet
Treasury Tag
Script paper

SPECIAL REQUIREMENTS
None

You may not start to read the questions printed on the subsequent pages until instructed to do so by the Invigilator.

1

When oil is emitted under sea ice in the form of a seabed blowout, a number of different interactions can occur. Describe the mechanisms by which oil reaches the ice underside from the sea floor, and describe its initial interaction with the ice surface in the cases of (a) fast ice *versus* moving ice, (b) a continuous ice cover *versus* a cover of broken floes, (c) first-year *versus* multi-year ice, (d) undeformed *versus* deformed ice. Deal with every combination of ice characteristics that yields a distinctly different physical interaction. Describe the mechanisms for the incorporation of an oil layer into a growing ice cover and its fate in spring and summer. What changes can be expected in these scenarios as a result of global warming effects?

Write down the equation that determines the thickness of an oil slick on the underside of a smooth flat floe as a function of surface tension parameters. Show that for crude oil of density 0.85 kg m^{-3} and oil-ice surface tension 1.5 N m^{-1}, the resulting oil layer will be less than 1 cm thick.

Consider two kinds of ice which pass over a blowout site: a smooth floe which will sustain a slick 1 cm thick, and a rough floe in which the average thickness in the roughness elements can reach 10 cm. Given that the oil is deposited from a rising plume of diameter 100 m, what is the mean speed of the floe above for which only discontinuous "painting" of the ice underside by the oil occurs, given oil flow rates of 200 and 2000 m^3 per day? For the four cases involved, calculate the percentage of the ice surface "painted" by the oil if the ice speed is 10 km/day, and describe the implications for the subsequent history of the oiled ice.

If you were responsible for installing equipment and resources at an Arctic site to counter the impact of an under-ice blowout, describe the measures that you would put in place and how they would operate at different stages of the emergency. Emphasise those aspects of the clean-up strategy where further research is needed to resolve unknown physical issues.

2

Write down the equations describing the energy exchanges at snow and ice surfaces and in the interior, leading to the prediction of thermodynamic sea ice thickness in the Maykut–Untersteiner model. Explain the concept of equilibrium thickness and sketch the sensitivity of the equilibrium thickness to (a) ocean heat flux, (b) annual snow fall, (c) changes in surface albedo.

Several mechanisms have been suggested as contributing to the recent thinning and retreat of Arctic sea ice in summer. Describe the mode of operation, and likely relative contributions, of (i) air temperature changes, (ii) increased heat in the Atlantic layer, (iii) erosion of the cold halocline, (iv) Pacific water inflow, (v) changes in the phase of the Arctic Oscillation, (vi) long-term thinning, (vii) albedo changes.

In recent summers the ice in the Beaufort Sea has lost 1.5 m through lower surface melt during the months June-September. Use your knowledge of the magnitudes of energy fluxes to estimate the equivalent average heat flux to the ice bottom and comment on the likely cause(s) for such a high value. Describe one feedback mechanism by which the summer warming of the ice-free parts of the Arctic Ocean is accelerating global warming.

3

Give the equations governing the free drift of ice floes and icebergs under wind forcing, water resistance and Coriolis force, with the magnitude of the Coriolis force being given by

$$F_c = 2m\,\omega U_i \sin\phi\,,$$

where m is ice mass, ω is angular velocity of Earth, U_i is ice velocity and ϕ is latitude. Calculate the turning angle between the surface wind and the equilibrium velocity of the ice, as a function of wind speed, air-ice and ice-water drag coefficients and the Coriolis parameter given above. What do the results tell us about the relative responses of ice floes and icebergs to the wind? Discuss the relevance of the results to iceberg occurrence in the Antarctic.

Describe the other forces that can act on a floating ice mass to affect its direction and speed of motion, and estimate their typical magnitude in relation to the main wind driver.

A rectangular iceberg of dimensions 300×200 km, with 100 m immersed depth, is found to be moving at 2 m/s under wind action. Its equivalent water drag coefficient is 4×10^{-3} over its horizontal base. Estimate whether attaching a powerful tug of bollard pull 300 tonnes (say 3×10^6 N) will significantly affect this motion and, if so, whether this suggests the feasibility of long-distance tows of icebergs.

4

Define a convective chimney and describe the locations in which open ocean convection occurs. Give a general description of the structure of ice-driven convective chimneys as observed in the Greenland Sea. What are the factors in the regional ocean and atmospheric circulation which lead to the generation of chimneys, and why have they become more unfavourable in recent years? Explain the salt flux mechanism for enhancing overturning in the chimney region.

Assuming that the uppermost 100 m of the ocean participates in surface processes, calculate the heat lost from the ocean surface, and the increase in density of surface water, when this water column is cooled from 0°C to -1.8°C (freezing point). Calculate the subsequent increase in density of the surface water when the same amount of heat is extracted from the surface at the freezing point to grow ice (assume complete loss of salt within the ice). What does this tell us about the relative efficacy of cooling and freezing in convection? List the other parts of the world ocean in which freezing enhances vertical water transfers. (Assume sea water density is 1025 kg m^{-3}, and that at low temperatures a density increase of 1 kg m^{-3} corresponds to a cooling of 10°C or a salinity increase of 1 psu.)

In the context of European climate change, what is the expected ocean-driven effect during the coming century associated with atmospheric warming of the Greenland Sea region?

END OF PAPER