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THE ROTATION OF THE EARTH AND PROCESSES NEAR THE AIR-SEA INTERFACE: SOME ASPECTS OF THE WORK OF V. W. EKMAN AND ITS CONSEQUENCES.

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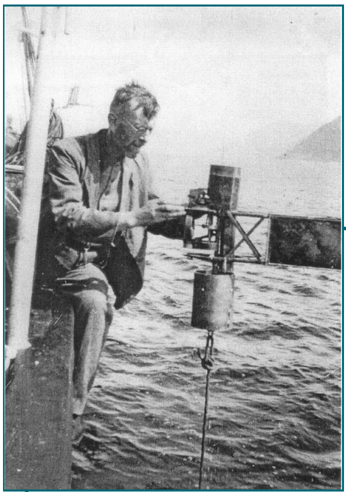

Figure 1: Ekman with one of his current meters.

Summary

The climatic conditions in the Arctic, and observations of the wind-induced drift of ice made in connexion with Nansen's "Fram" expedition, led to the discovery one hundred years ago, by Vilhelm Bjerknes' pupil, V. W. Ekman, of the importance of the Earth's rotation in limiting the depth of the wind-induced shear current in the ocean.

We provide an overview of the impact of Ekman's theory and other work on climate-related processes. These include the Ekman spiral—the helical rotation of the velocity vector, in atmospheric and oceanic boundary layers, and the resultant Ekman pumping: vertical motions in the water column and the divergence of the flow in the presence of a rotational wind stress field. These effects are important in the presence of sea ice, because of the differences in drag coefficient between ice-covered and open-water areas. The magnitude and direction of the surface current relative to the wind vector is also influenced by the presence of surface waves and the behaviour of the turbulent flow in the near-surface layer of the ocean. Although the meridional heat transport in the Nordic Seas may be dominated by the thermohaline circulation, the wind-induced flow and its spatial and temporal variability also has a substantial effect. Ekman theory consequently plays a very significant role in high-latitude climate dynamics.

Introduction

Observations of the drift of the vessel Fram as it was frozen into the ice during Nansen's polar expedition of 1894–1896 [21] provided significant new insight into the response of the surface layer of the ocean to wind forcing. Nansen found that the drift of the ice was on average directed between 20 and 40 degrees to the right of the wind direction. He explained this fact as a consequence of the Earth's rotation, and predicted that the current vector would spiral clockwise with increasing depth. At Nansen's request, Vagn Walfrid Ekman (1874–1954) investigated the problem mathematically, and published the results in a series of papers in three languages [4, 6, 7].

Ekman's achievements

Ekman showed how the rotation of the earth influenced the way that the ocean currents responded to the force of the wind, using the concept of a turbulent 'eddy viscosity' coefficient ν_E. For constant ν_E, he showed that in the steady-state limit, the following formulae give the current at depth z:

$$
\begin{aligned}
u &= V_0 e^{-\alpha z}\cos[(\pi/4)-\alpha z],\\
v &= (f/|f|)V_0 e^{-\alpha z}\sin[(\pi/4)-\alpha z], \qquad (1)\\
\alpha &= [|f|/(2\nu_E)]1/2, \qquad f = 2\omega\sin\phi\\
V_0 &= \tau/(\rho\nu_E\alpha\sqrt{2}),
\end{aligned}
$$

where u and v are the horizontal Cartesian components of the current, V_0 is the magnitude of the surface current, ω is the angular speed of rotation of the Earth, f is the Coriolis parameter, ϕ is the latitude, ρ the water density, and $(0,\tau)$ the stress induced by the wind at the sea surface (here assumed to be directed along the y-axis).

The current in (1) decreases with depth, and the current vector traces a spiral path (*Ekman spiral*), the frictional influence of the wind being restricted to a near-surface *Ekman layer*: such layers also occur near the sea bottom and in the atmosphere. The steady-state mass flux ('Ekman transport') in the Ekman layer is $\tau/(\rho|f|)$ directed 90 degrees to the right of the wind stress in the Northern hemisphere, independent of the eddy viscosity. A rotational spatial gradient of the wind stress (curl) will induce a divergent Ekman transport, leading to upwelling or downwelling in the interior (*Ekman pumping*).

Ekman also made other significant contributions to oceanography: He authored a comprehensive experimental and theoretical study of the 'dead water' phenomenon, in which vessels have their progress impeded by the generation of internal waves [5]. He participated in deep-ocean expeditions [12], current measurements from which paved the way for today's comprehensive direct surveys of ocean circulation and climatic variability, and designed oceanographic instruments, including an insulated water sampling bottle [21] and a series of mechanical current meters [10, 12].

As professor of mathematics at the University of Lund, he published a textbook on mechanics [8], which contains discussions of the philosophical basis of the subject, illustrated by biographies of Galileo, Newton, and Huygens. Some of the exercises book refer to geophysics and polar exploration: in the first exercise, the reader is asked to calculate the mean velocity of an icebreaker. Ekman also took part in discussions on the philosophy of religion, publishing a pamphlet on how belief in a deity can be reconciled with scientific knowledge [11].

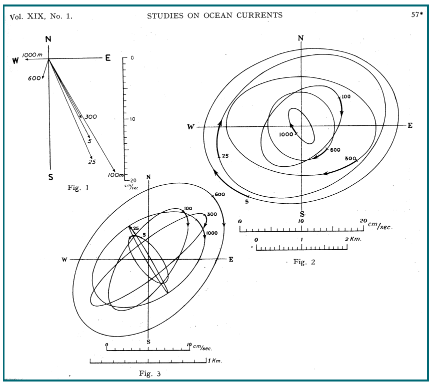

Figure 2: Ekman's analysis of current measurements from the North Atlantic [12], showing mean current ('Fig. 1'), diurnal (inertial) oscillations ('Fig. 2'), and semidiurnal tides ('Fig. 3').

Ekman's work, applied to the coupled atmosphere–ocean boundary-layer system, can be extended to within decimetres of the sea surface by taking surface waves into account, either directly [17, 18, 19, 23], or via a parameterized inertial coupling mechanism [1, 2]

Application to climate-related processes

Ekman theory arises historically from phenomena observed in polar exploration, so it should be relevant for high-latitude climate. The ocean thermohaline circulation may provide the greater part of the meridional heat transport, and varies at much longer time scales than the wind-driven circulation. Nevertheless, the atmospheric circulation will be influenced by secular changes in sea-surface temperature (SST) and sea-ice cover.

The application of Ekman dynamics to ocean circulation processes in the northern polar regions, encompassing the Arctic Basin and Nordic Seas, can be divided into three main categories: the wind-driven flow; the interior and bottom circulation; and processes related to sea ice. Measurements of the Barents Sea inflow from the Norwegian Sea [16] indicate that Ekman transport makes a significant contribution to the observed currents, and coastal downwelling during the winter season. In agreement with Ekman's analysis, the Ekman transport will, by its action on the sea-level gradient, drive a flow throughout the water column. The spiral current profile within the bottom Ekman layer leads to Ekman veering, in which the current above the bottom is directed to the right of the current near the bottom, and leads to a spreading out of gravity currents of dense water, such as in the Faroe Bank Channel outflow [20], and in the outflow from regions such as Storfjord (Spitsbergen) where a dense saline overflow generated by freezing-induced brine release descends the continental slope [13].

The wind-induced drift of sea ice offshore, taking account of the Ekman turning angle, enables the opening of coastal polynyas, in which freezing at the ocean surface can take place [15], and downward convection of the brine which is released. Conversely, ice melting releases freshwater which will rapidly suppress the convection. Other processes associated with sea ice, include complex effects of the convergence, shear, and divergence of both the Ekman transport associated with the wind stress, and currents set up by impinging surface waves [24]. The divergence of sea ice motion, and the wind-driven export of sea ice from the Arctic and the Nordic Seas, in both of which processes Ekman dynamics are a controlling factor, are important for the ventilation of the ocean interior, as measured by the observed distribution of chlorofluorocarbons [22].

At high southern latitudes, the Antarctic Circumpolar Current dynamics depend on the relation between the wind driven and the thermohaline circulation, as stated by Ekman [9] (English translation by Welander [25]). Ekman stated, 'One has had little success in the discussion of the question whether the wind or the internal equilibrium changes represent the most important cause of the ocean currents', and even after 80 years this problem still remains on the agenda. Gent et al [14] suggest that 100 Sv is driven by the meridional Ekman transport (wind stress forcing) and 30 Sv is driven by the northward flow of Antarctic Bottom Water, whereas Cai and Baines [3] found that, the wind stress forcing accounts for 40 Sv and the thermohaline forcing accounts for 80 Sv.

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