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On the influence of Heat Fluxes on Storms

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ABSTRACT. The influence of eddy fluxes of heat at the interface of the oceans and the atmosphere has been numerically estimated in the case of a North Atlantic cyclone. The role played by such fluxes is discussed. It is shown that the heat sources and sinks associated with tropospheric features at the earth's surface exert marked influences on the development of mobile pressure systems.

1. Introduction

Eddy fluxes of real and latent heat across the earth-atmosphere interface can exert profound influence on cyclone development, as repeatedly stressed by Petterssen (1950, 1956 1959, 1960). Mobile systems in the atmosphere are modified by heat sources and sinks and sometimes substantially so. It is, therefore, important to include the effects of such transfers of heat in predictions of the behaviour of weather systems, as pointed out by Petterssen and Calabrese (1959) in their study of the effects of water bodies on the pressure configuration and precipitation patterns in the vicinity of the Great Lakes. More recent investigations by Petterssen and collaborators (under publication) have provided numerical estimates of these influences, which substantiate earlier conclusions. While the amounts of energy involved in radiative and eddy transfers should be balanced against frictional dissipation over extended periods of time, the above investigations have shown that large and systematic imbalances exist on space and time scales of importance for cyclone development. The purpose of the present investigation is to apply the Petterssen techniques for computing eddy fluxes of latent and sensible heat and to demonstrate their influences on an interesting cyclone development on the north Atlantic Ocean.

2. The formulae

For assessing the possible modification of developing motion systems, the heat gained or lost by the atmosphere is more important than that transferred into or out of the underlying surface. When bulk surface temperatures are in adjustment, no transfer of energy across the interface takes place and the typical diurnal cycle operates. But when horizontal motion of an air mass of different temperature or *invasion* takes place, this adjustment is disturbed. Heat will then be transferred from the hotter to the colder medium. For air in motion over the ocean, the eddy flux of sensible heat (H_s) can be computed by the formula —

$$H_s = F(V)\, f(T_s - T_a)$$

where V is the wind speed and T_s and T_a are the temperatures of the sea and the air at the interface.

The form of the functions F and f depends on the prevailing conditions. For strong winds, such as those which prevail over oceans in the middle latitudes, we may postulate the existence of a fully forced convective regime following Priestly (1959) so that

$$H_s = \rho\, C_p\, C\, V\, (T_s - T_a) \qquad (1)$$

where ρ is the density of the air at the interface, C_p is the specific heat of air at constant pressure, V is the wind speed in knots at the deck level where observations on ships are made, T_s and T_a are the sea temperature and the air temperature at deck level and C is a numerical constant, the value of which depends on units used.

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If H_s is expressed as cal cm^{-2} min^{-1}, V in knots and T in degrees Fahrenheit and ρ is replaced by the standard value of $1 \cdot 25 \times 10^{-3}$ tons m^{-3}

$$H_s = 1 \cdot 30 \times 10^{-3} \, V \, (T_s - T_a) \quad \text{cal cm}^{-2} \text{ min}^{-1} \qquad (2)$$

The numerical constant in equation (2) was first determined by Jacobs (1942) from considerations of energy balance; it has recently been supported by independent data provided by Deacon, Sheppard and Webb (1956). It is now generally conceded that this coefficient is satisfactory for use in connection with large scale processes in windy regimes although the value may be doubtful in the case of highly stable stratifications.

The rate of evaporation from the ocean surface, or the upward eddy flux of latent heat at a short height above the sea surface can be computed from the formula

$$H_L = 2 \cdot 64 \times 10^{-3} \, V \, (e_s - e_a) \quad \text{cal cm}^{-2} \text{ min}^{-1} \qquad (3)$$

where H_L is the eddy flux of latent heat, e_s is the saturation vapour pressure in mb corresponding to T_s and e_a is the vapour pressure corresponding to the temperature of air at the observation level.

The constant in equation (3) is based on rather meagre data. The value used here is the one provided by Swinbank (1960), who obtained it by combining the data of Sheppard (1958) and Marciano and Herbeck (1952). This however, agrees with that derived independently by Budyko (1956).

Though the numerical values of the constants used in equations (2) and (3) may not be accurate, there can be little doubt that the configuration of the synoptic patterns of the eddy heat fluxes are entirely representative. The transfers of real and latent heat can be computed from customary synoptic data. The present study is confined to the middle latitudes of the North Atlantic as a sufficiently dense network of data is available from ships' observations in this area.

The rate of dissipation of kinetic energy at the ocean interface has been shown by Petterssen and Bradbury to be so small compared to the fluxes of latent and sensible heat that it is of no significance for prediction over relatively short periods of time.

3. Analysis and Evaluations

Ships' data were used in the present analysis and evaluations. The sea temperatures, of course, refer to the sea level while the temperatures and dew-points of the air refer to a height of about 8 metres, which is the deck-level where observations are usually made on board the ships.

To obtain H_s the fields of each of the variables V, T and T_a were analysed in detail by drawing isotachs and isotherms and brought into harmony with the frontal and air mass analyses. To obtain the fields of e_s and e_a the observed sea surface temperatures and dew-point temperatures at deck-level were analysed and converted into vapour pressures in millibars. Finally, the required differences and products were obtained by graphical operations and the resulting fields of H_s and H_L analysed by drawing isopleths of heat flux at intervals of $0 \cdot 2$ cal cm^{-2} min^{-1}.

4. The synoptic situations

The storm chosen for this study was one which displayed intense and rapid development not foreshadowed by customary sea-level and upper air analyses. It originated as a cyclonic wave off the east coast of North America at 0000 GMT on 25 November 1958. The relevant surface chart is shown in Fig. 1(a). In Figs. 1(c) and 1(d) are shown the 0000 GCT 500-mb contour and 1000-500 mb thickness charts. The latter charts are not suggestive of the possibility of any marked development of the wave disturbance off the north Atlantic Coast. Apart from this disturbance, an intense and well-developed cyclone is present on the eastern North Atlantic Ocean to the south of Greenland. The two systems are so far apart that it may justifiably be assumed that they developed more or less independently of each other.

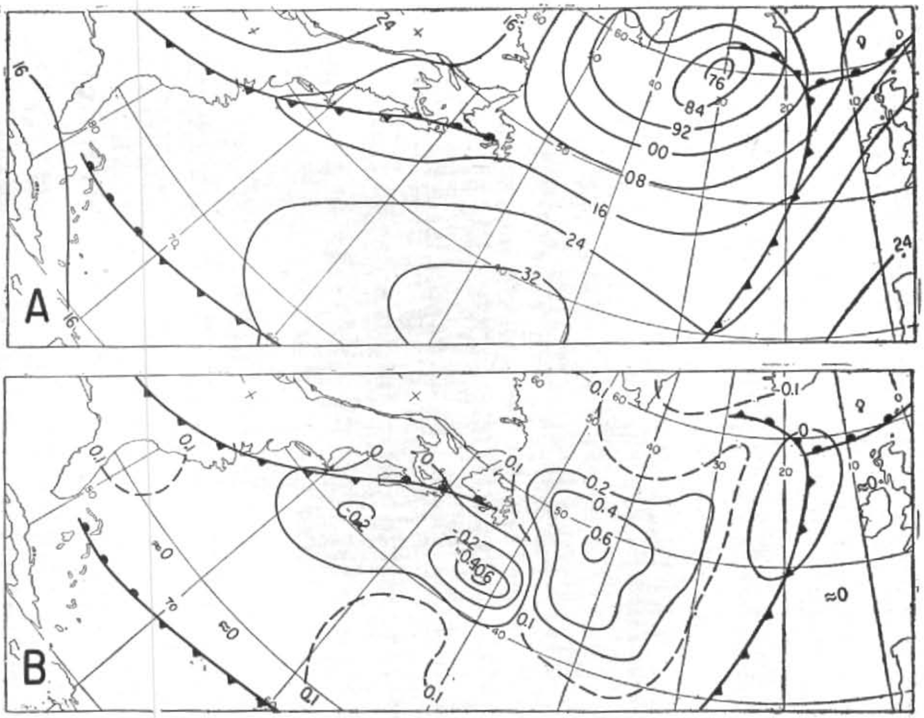

Fig. 1 (a, b). 0000 GCT, 25 November 1958

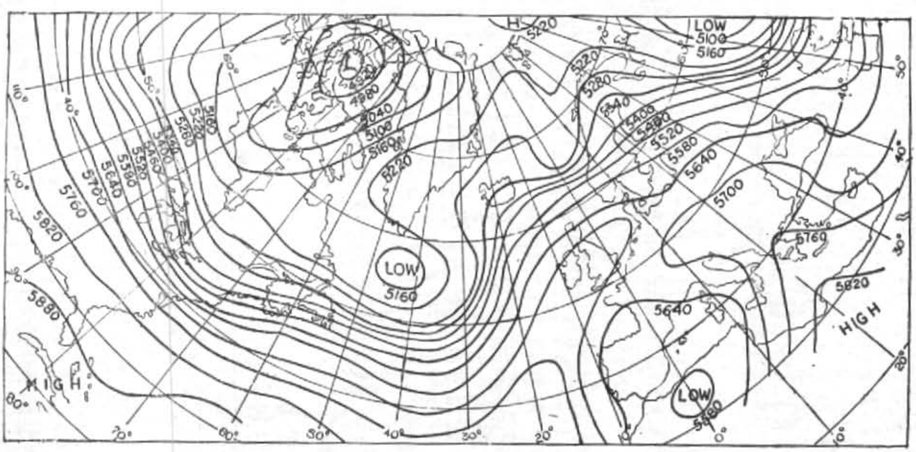

Fig. 1 (c). 0000 GCT, 25 November 1953, 500 mb

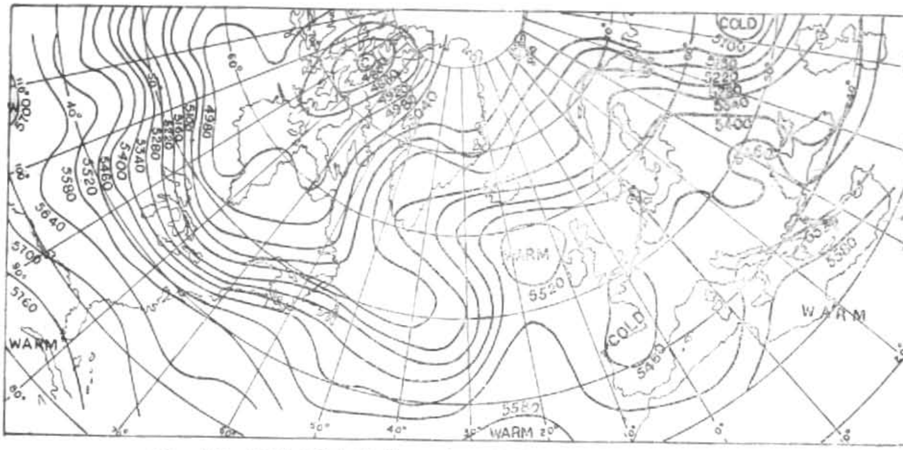

Fig. 1(d). 0000 GCT, 25 November 1958, 1000-500 mb thickness

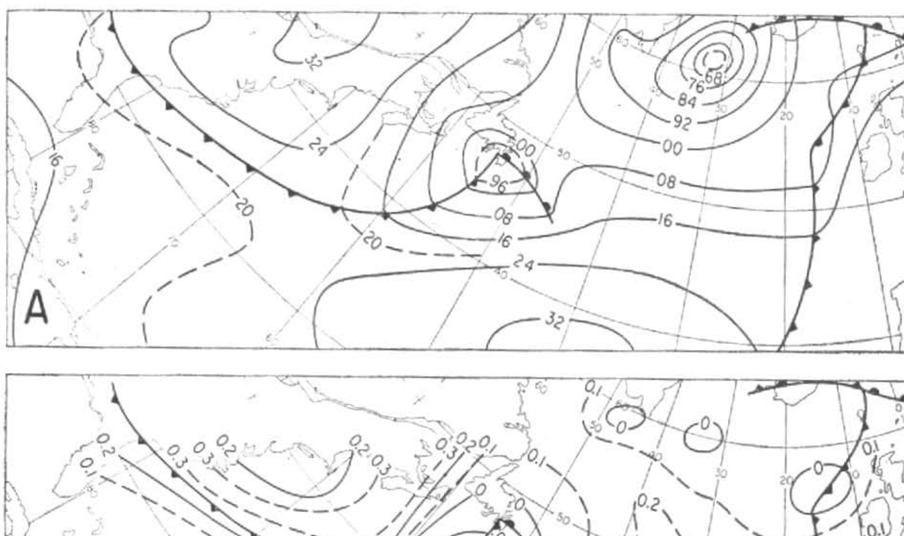

Fig. 2 (a, b). 1200 GCT, 25 November 1958

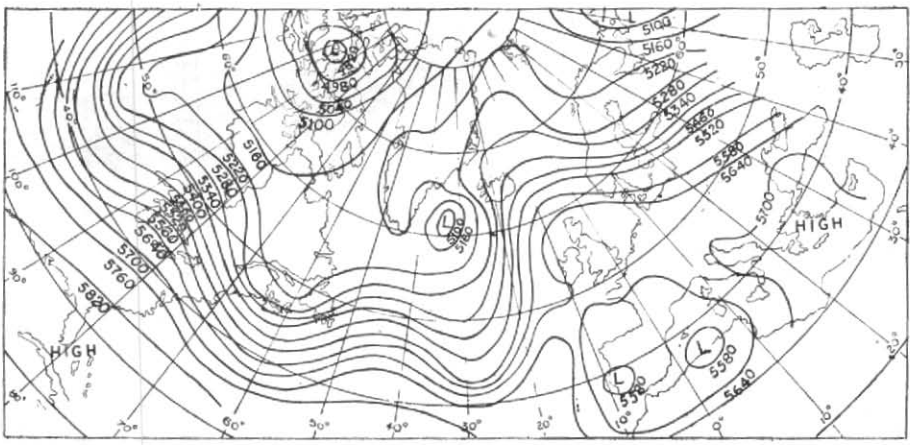

Fig. 2(c). 1200 GCT, 25 November 1958, 500 mb

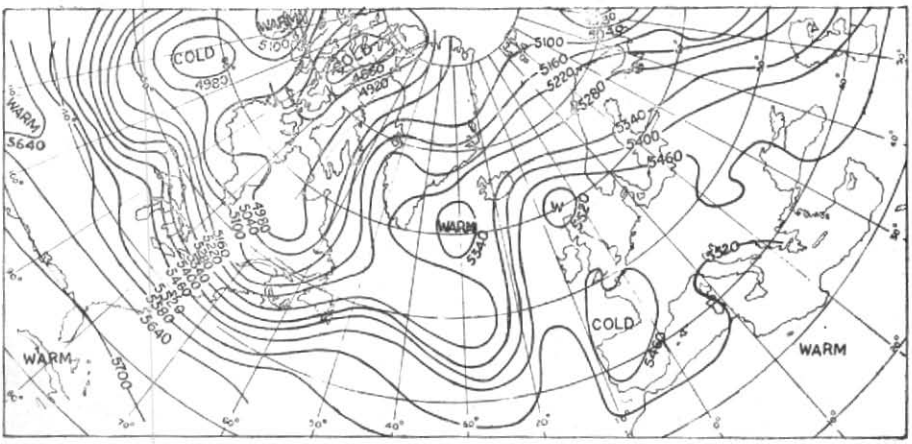

Fig. 2(d). 1200 GCT, 25 November 1958, 1000-500 mb thickness

The corresponding 1200 GCT charts of 25 November 1958 are reproduced in Figs. 2(a), 2(c) and 2(d). Notwithstanding the absence of any indication on the 0000 GCT charts, there was intense development of the wave off the east coast of North America into a deep warm sector storm, in the short intervening period of 12 hours. The earlier disturbance moved rapidly northeast and is seen on the 500 mb and thickness charts as a warm-core cyclone. In Figs. 3(a), 3(c) and 3(d) are shown the location of the cyclone in its most intense stage of occlusion at 1200 GCT on 26 November 1958 and the associated 500 mb contour and thickness patterns.

5. Discussion

The primary purpose of this presentation is a discussion of the patterns of the eddy fluxes of sensible and latent heat in relation to the development of mobile synoptic systems. The rapid deepening by over 30 mb of the nascent wave under study into a warm sector storm during the short interval of 12 hours from 0000 to 1200 GCT on 25 November 1958

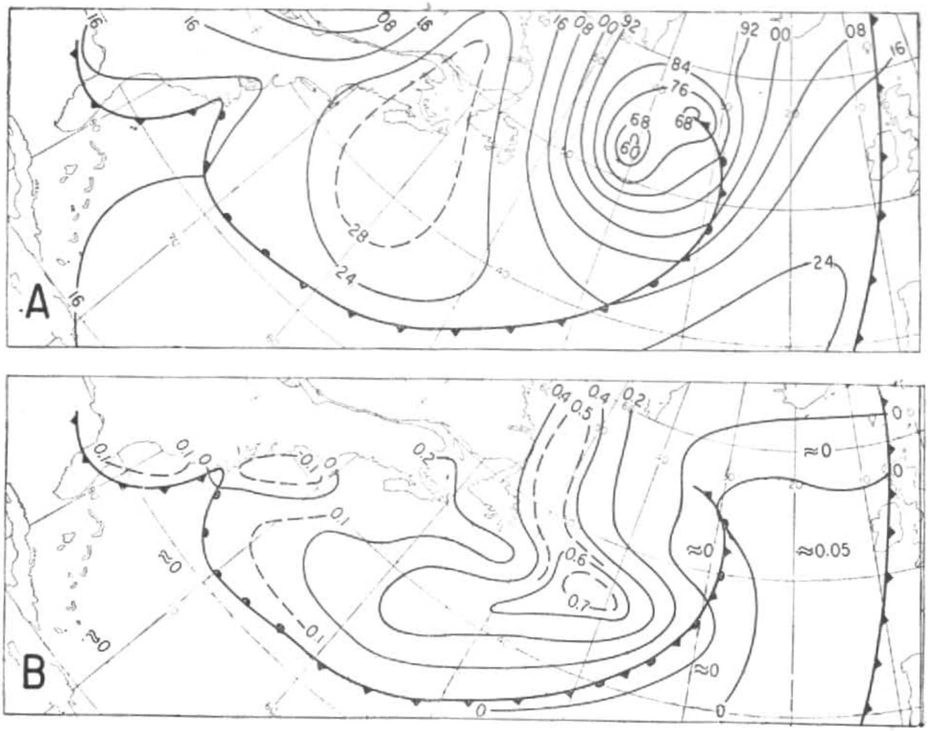

Fig. 3 (a, b). 1200 GCT, 26 November 1958

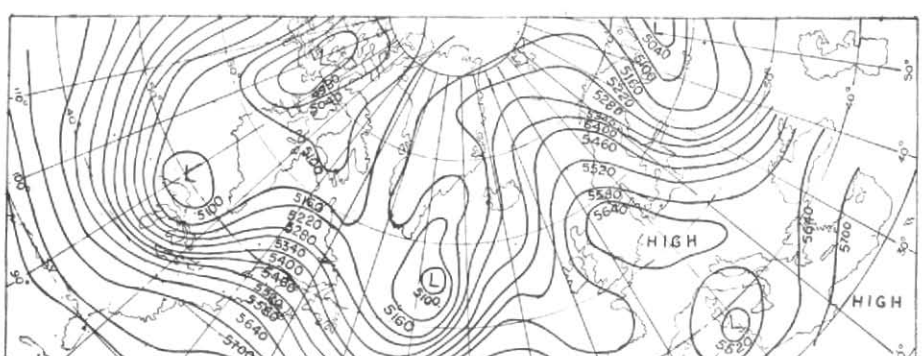

Fig. 3(c). 1200 GCT, 26 November 1958, 500 mb

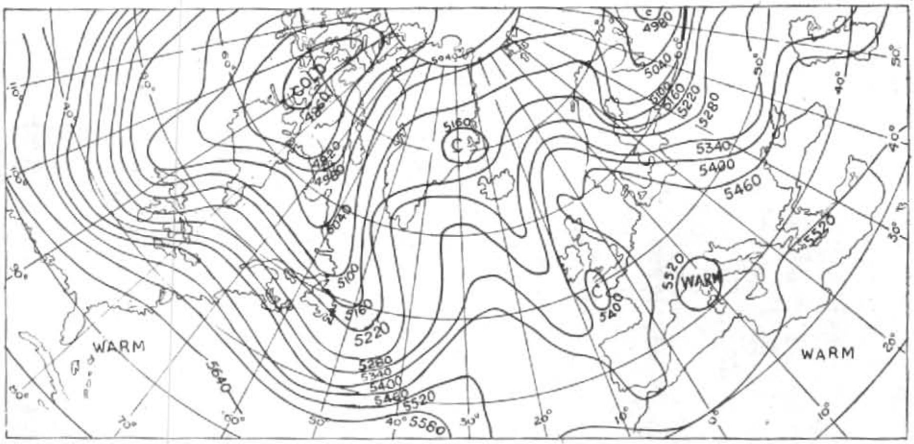

Fig. 3 (d). 1200 GCT, 26 November 1958, 1000-500 mb thickness

was not foreshown by either the thickness or the 500-mb charts of 0000 GCT. There are no upper air ascents between 0000 and 1200 GCT to gauge the cyclogenetic potentialities in the intervening period. The subsequent rapid intensification of the warm-sector cyclone into an occlusion during the following 24 hours was another interesting feature of this disturbance. Heuristically, the contribution of eddy fluxes of sensible and latent heat towards this consummation of the nascent wave merit careful appraisal.

Petterssen and Bradbury (1960) have found that, in the winter season, the eddy fluxes of sensible heat display significant maxima in the rear of cyclones and minima with negative heat flux in northward moving warm air. They also state that the eddy fluxes of latent heat are, on the whole, of weak intensity and small horizontal extent. The author has found this to be so. Further, the patterns of eddy fluxes of latent heat bear close similarity to those of sensible heat. It was not, therefore, felt worthwhile to reproduce the charts of eddy fluxes of latent heat associated with the storm under study. Charts showing the fluxes of sensible heat corresponding to the nascent wave, warm sector and occlusion stages of the storm are shown in Figs. 1(b), 2(b) and 3(b).

5.1. *The nascent wave stage*

The most noteworthy feature of Fig. 1(b) is the presence of an area of negative heat flux of 0·6 units (cal cm^{-2} min^{-1}) south of Newfoundland. As Priestly has stated, the conductive capacity of stirred water is 100 times larger than that of stirred air so that the ocean may be regarded as an infinite sink of heat. While downward fluxes are relatively frequent over the Grand Banks, numerical values much in excess of 0·2 units are rare. In the present case, there is a wide area of over 50 degrees square, in which the downward fluxes are in large excess of 0·2 units. The configuration of the pattern is such that a large negative contribution to the rate of cyclone development is evident (Petterssen 1956). Nevertheless, as seen from Fig. 2 (a), a moderate positive development did take place. Though it is not possible to separate the effects of the various processes that contribute to cyclogenesis, it appears beyond doubt that, in this case, the heat sink reduced the intensity of the development as compared with what it could have been had the process been adiabatic.

5.2. *The warm-sector stage*

The synoptic situation at 1200 GCT on 25 November 1958 shows that the rate of development during the preceding 12-hour period was very great, the centre having deepened by more than 30 mb and the vorticity having increased by a several-fold factor. As the storm moved away from the Great Banks into the open North Atlantic Ocean to the southeast of Newfoundland the downward flux of heat diminished appreciably in the warm sector, a feature making for positive contribution to cyclogenesis relative to the nascent wave stage.

5.3. *The occlusion stage*

As the cyclone centre moved further eastward, the downward flux disappeared altogether and was replaced by an upward flux with large positive contribution to vorticity development (Fig. 3b). Since this took place to the rear of the centre, one would expect strong asymmetry in the vorticity field and that this would be in the cold rear rather than at the apex of the occlusion. The development seen in Fig. 3(a) strikingly vindicates this expectation, the maximum deepening by nearly 60 mb occurring to the southwest of the apex of the occlusion towards the centre of maximum upward flux of sensible heat.

6. Conclusion

The present study emphasises the importance of the role played by heat sources and sinks associated with the tropospheric features of the earth's surface in the development of pressure systems. The dimensions of the patterns of heat flux are comparable with those of the synoptic scale motion systems. It appears plausible that the eddy fluxes of heat exert marked influence on the development of extra-tropical cyclones. These fluxes have, therefore, to be given due weight in prognosticating the development of mobile cyclonic systems.

7. Acknowledgements

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