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A comparison of two methods for estimating sensible heat flux in oceanic extratropical synoptic-scale systems

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ABSTRACT

The advective method for estimating the sensible flux from the ocean to the atmosphere, devised by Bullock & Johnson (1972) for use in data-sparse oceanic regions, is compared with the bulk aerodynamic method. The results from a case study over the North Atlantic indicate that the method of Bullock & Johnson approximates the spatial distribution obtained by the aerodynamic method but underestimates the magnitude of the sensible heat flux.

1. Introduction

The eastern coasts of the continents of the northern hemisphere and the entire coastline of Antartica are regions where frequently, in the wintertime, extremely cold continental air moves over relatively warm ocean water. When this happens, there is a very strong transfer of sensible heat from the ocean to the atmosphere at scales that might be termed the synoptic scale. A number of studies have shown that this synoptic-scale transfer of sensible heat is significant in the cyclogenesis that occurs in these regions (Petterssen, Bradbury & Pedersen, 1962; Winston, 1965; Gall & Johnson, 1971; Bullock & Johnson, 1972; Min & Horn, 1974). For this reason, to fully understand its role in cyclone development, accurate estimates of the synoptic-scale flux of sensible heat in the cold air mass are necessary. Furthermore, the sensible heat transfer represents an important source of this form of energy for the mid-latitude global circulation; hence, a knowledge of the magnitude and spatial distribution of this transfer is important for a basic understanding of climate.

The most practical method for estimating the synoptic-scale transfer of sensible heat from the ocean to the atmosphere is the bulk aerodynamic method (e.g., Deacon & Webb, 1962; Roll, 1965). However, in applying this method, accurate estimates of the low-level air-sea temperature difference are required, and, in regions where air temperature data are sparse, this information may not be available. This limitation effectively restricts the utilization of the bulk aerodynamic method to ocean areas with considerable ship traffic.

Recently Bullock & Johnson (1972) studied the generation of available potential energy by the sensible heat transfer from the ocean surface in extratropical cyclones near the Antarctic continent. Since the Antarctic oceans are a region of very little data, utilization of the bulk aerodynamic method was impractical; hence, they were forced to devise a method to estimate heat flux from the ocean in data-sparse regions.

Their method essentially required only a knowledge of the sea-surface water temperature, the surface pressure, and the depth of the mixed layer[1] near the ocean surface. This information may be obtained from relatively small amounts of ship, synoptic and upper-air data. For example, sea-surface temperatures vary slowly with time and therefore may be obtained from climatological data. Surface pressure can be inferred from satellite pictures and the few ship reports that are available. Finally, the depth of the mixed layer can be aproximated from fields that have been systematically analyzed to maintain three-dimensional consistency of the cyclone scale (Gall & Johnson, 1971).

[1] The mixed layer is defined as the layer of air next to the ocean surface where adiabatic lapse rates are produced and maintained by the convection of heat from the ocean surface.

Because of the assumptions used to derive the method of Bullock & Johnson, it is uncertain just how realistic its estimates of the synoptic-scale transfer of sensible heat will be. The purpose of this paper is to show that the estimates derived from this method are indeed realistic. To do this, a comparison is made between the estimates given by the method of Bullock & Johnson and those given by the bulk aerodynamic method for a region of the North Atlantic. The data density in this region is adequate for use of the bulk aerodynamic method.

The reader should note that the comparison to be made here is at best only relative, since a number of assumptions are also required to derive the bulk aerodynamic method. In fact, Gall & Johnson (1971) showed that considerable uncertainty is intrinsic to the bulk aerodynamic method, since its sensible heat flux estimates varied by a factor of at least two, depending on the empirical relations used to estimate the drag coefficient and the ten-meter wind speed. The comparison, however, will be made with the heat-flux estimates considered by Gall & Johnson to be most realistic for their case study; therefore, it is felt that the results presented here will establish the usefulness of the Bullock & Johnson technique.

2. The advective and bulk aerodynamic models of sensible heat flux

Bullock & Johnson (1972) used four assumptions to determine their diagnostic advective model[1] for estimating sensible heat flux. These assumptions are: (1) the mixed layer remains adiabatic in the presence of intense convection, (2) the air and sea-surface temperatures are equal, (3) the sensible heat flux vanishes at the top of the mixed layer, and (4) the component of the geostrophic wind along the sea-surface temperature gradient is an estimate of the mean wind component of the mixed layer along the sea-surface temperature gradient. With these assumptions, the expression for the sensible heat flux is

$$F_0 = \frac{c_p(P_0^{1+\kappa} - P_t^{1+\kappa})}{gP_{00}^{\kappa}(1+\kappa)} U_{g\eta} \frac{\partial \theta_s}{\partial \eta}, \qquad (1)$$

[1] Hereinafter called the advective method.

where the notation is presented in the Appendix. An equivalent relation is

$$F_0 = \frac{c_p(P_0^{1+\kappa} - P_t^{1+\kappa})}{gP_{00}^{\kappa}(1+\kappa)} U_{g0} \nabla \theta_s \qquad (2)$$

In this expression, the sensible heat flux is the amount required to maintain exactly adiabatic conditions in association with temperature advection within the mixed layer. Backing of the wind with height due to a thermal wind component does not produce erroneous estimates, since this component is normal to the gradient of the temperature distribution in the mixed layer. A detailed derivation of (1) is presented in Bullock & Johnson (1972).

The sensible heat flux by the bulk aerodynamic method is

$$F_0 = \rho c_p C_a(z)(\theta_s - \theta_0)U(z). \qquad (3)$$

In this technique, the flux is determined by the air-sea temperature difference and the wind at some height, z, for which the drag coefficient $C_d(z)$ is specified. The procedures for estimating $C_d(z)$, $U(z)$ and the top of the mixed layer in this application are discussed in Gall & Johnson (1971).

3. Comparison of the sensible heat flux estimates

The sensible heat flux at two time periods, 0000 Z and 1200 Z, February 14, 1968, was computed for a large region of the Western Atlantic. The surface synoptic pattern for these periods, depicted in Figs. 1A and 1C, was dominated by a very large area of cyclonic flow covering much of eastern Canada and the Western Atlantic. Embedded within this flow was a rapidly developing storm south of Newfoundland and a stream of very cold air flowing southward across the Gulf Stream along the east coast of the United States.

The spatial distributions of the sensible heat flux from the ocean computed by the two methods are shown in Fig. 2 for both time periods. Both methods indicate a large area of strong heating along the east coast of the United States and behind the cold front. The bulk aerodynamic method estimates high flux values along the East Coast, extending almost as far south as Florida, whereas the advective method yields less heating in the southern

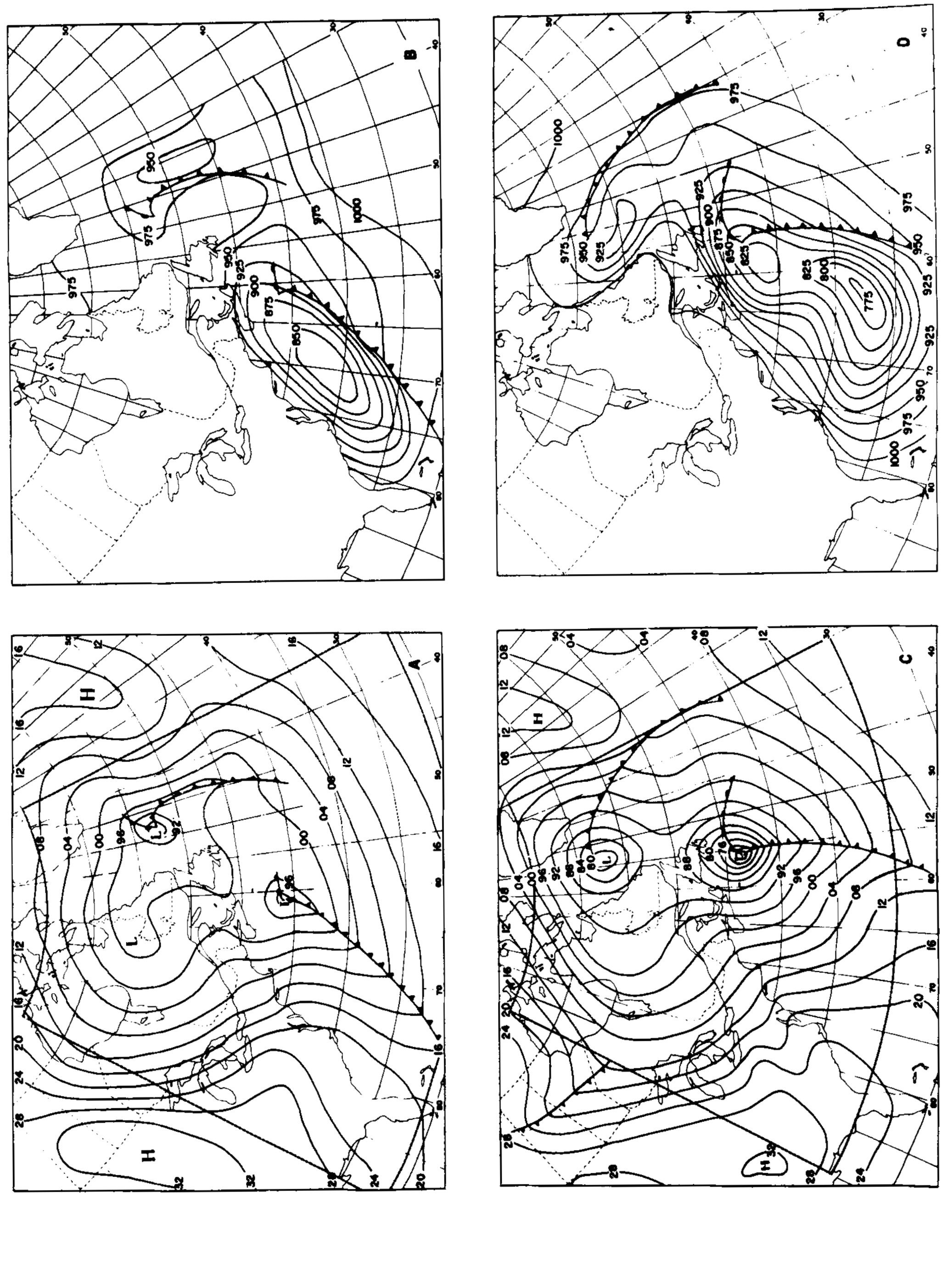

Fig. 1. Surface pressure analysis (mb) for 0000 Z (Fig. A) and 1200 Z (Fig. C) on February 14, 1968. Pressure (mb) of the top of the mixed layer at 0000 Z (Fig. B) and 1200 Z (Fig. D) for February 14, 1968.

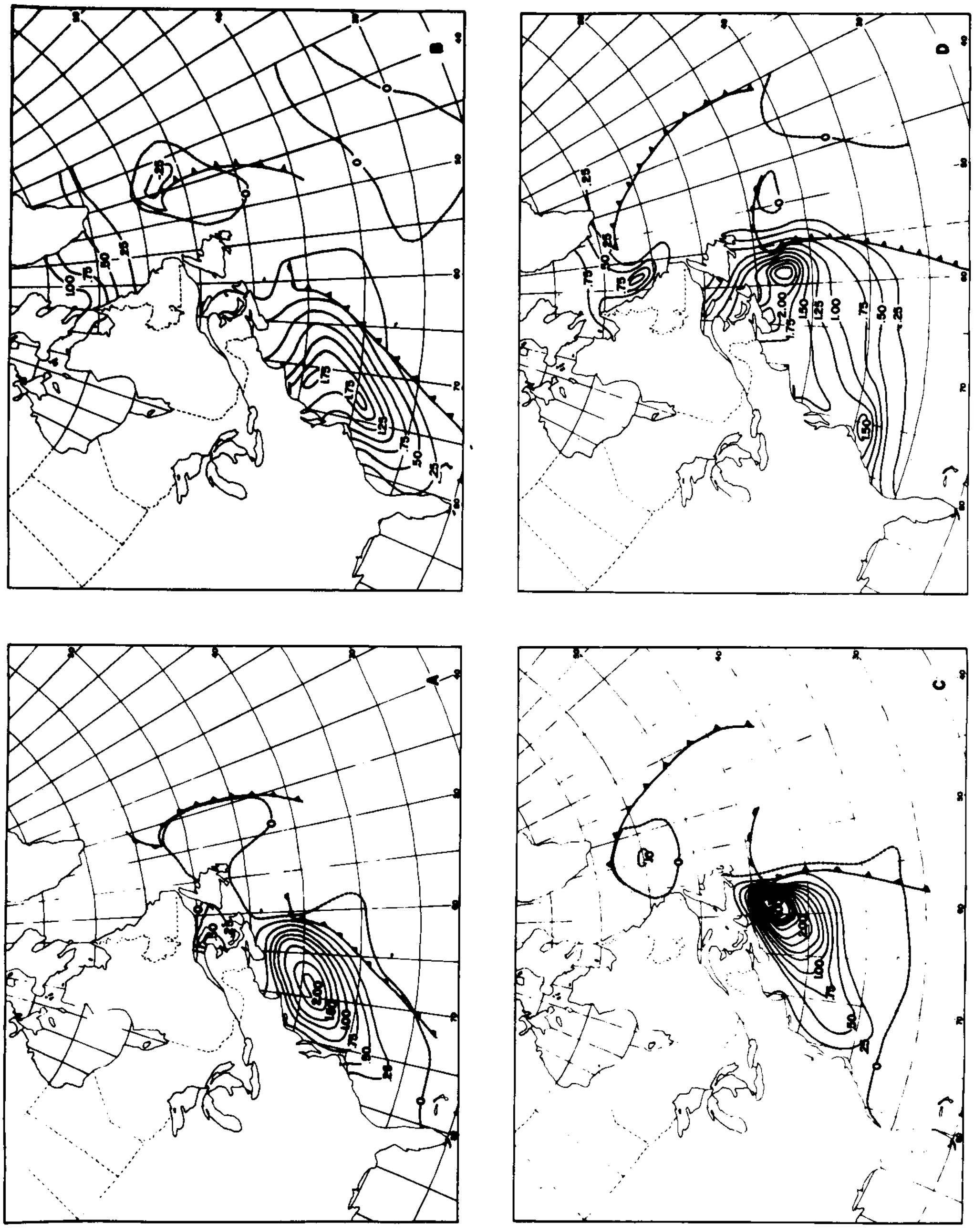

Fig. 2. The sensible heat flux (cal cm^{-2} sec^{-1} × 10^{-2}) estimated by the advective method at 0000 Z (Fig. A) and 1200 Z (Fig. C) and by the bulk aerodynamic method at 0000 Z (Fig. B) and 1200 (Fig. D) for February 14, 1968.

portion of the cold air mass. To the north, both methods produce high positive values; however, the advective method indicates a maximum southwest of the major storm center that is nearly twice the value from the aerodynamic method. Elsewhere the two methods generally agree, except in the regions where the aerodynamic method indicates a negative flux. Since the assumptions leading to the advective method are valid only for upward sensible heat flux, the advective model cannot be used to estimate downward heat flux. This deficiency is minor, since the stratification accompanying the transport of warm air over a cold ocean suppresses the turbulent heat transfer, and therefore the magnitude of this transfer in these regions is unimportant for the synoptic scale.

In the derivation of the advective model, it is assumed that the heat entering the base of the atmosphere diffuses upward instantaneously in the maintenance of the adiabatic lapse rate of the mixed layer. In reality, however, a superadiabatic layer develops near the ocean surface; hence, the growth of the depth of the mixed layer, as the cold air mass flows seaward towards warmer sea-surface temperatures, may occur at a slower rate than the assumptions imply. Where there is a strong superadiabatic layer, the bulk aerodynamic method will indicate a strong upward heat flux. However, in such a region, the depth of the mixed layer will be thinner than it would be if the lapse rate were always maintained at adiabatic. Thus, in such a region, the advective method, which depends on the depth of the mixed layer, will probably provide a lower estimate of the heat flux than will the bulk aerodynamic method. A situation like this usually develops near the coastline, where the cold air first moves over the water. This may account for the discrepancies between the two heat flux estimates near the coast of the United States, south-west of the major storm center.

At 1200 Z, February 14, both methods calculate a large maximum of heating just southwest of the strong storm center east of Newfoundland. The strong northwest winds associated with the storm in that region rapidly move cold air towards relatively warm sea water. However, in this region of strongly curved cyclonic flow, the geostrophic wind approximation will give an overestimate of the temperature advection; thus, the advective method will be likely to overestimate the heat flux. Use of the gradient wind approximation would probably provide estimates by the advective method which would be in closer agreement with the bulk aerodynamic method in such a region.

Table 1 presents the average heat fluxes for the area delineated by the dashed rectangles in Fig. 1. Note that the estimates of the average heat flux by the advective method are lower than those given by the aerodynamic method. This is a reflection of the overall distribution of lower flux estimates given by the advective method when compared to the aerodynamic method depicted in Fig. 2. Both methods indicate an increase in the upward heat flux between 00 Z and 12 Z, although the increase indicated by the advective method is less than that indicated by the aerodynamic method.

Table 2 shows the generation of available potential energy by the sensible heating determined from both the advective and bulk aerodynamic methods for 1200 Z, February 14. The available potential energy for these estimates was defined for a vertically walled volume bounded by the dashed lines in Fig. 1. Upper and lower bounds for the generation of available potential energy in this volume are presented, due to the uncertainty in the nature of the turbulent transfer of energy within the planetary boundary layer (see Gall & Johnson, 1971). The actual generation is expected to lie within these bounds.

The generation computed using the advective method is about half of that computed using the bulk aerodynamic method. Assuming that the generation can be approximately determined from

Table 1. *Average heat flux* ($W \cdot m^{-2}$), *February 14, 1968*

Time Period	Advective Method	Bulk Aerodynamic Method
0000 Z	44.8	64.5
1200 Z	50.7	109.7

Table 2. *Generation of available potential energy* ($W \cdot m^{-2}$), *1200 Z, February 14, 1968*

Bounds	Advective Method	Bulk Aerodynamic Method
Upper	1.574	2.81
Lower	0.614	1.59

the average heating, then the 30–50% lower estimates of the average heat flux by the advective method will account for this lower estimate of the generation. Hence, the estimates of the generation by sensible heating in a southern-hemisphere cyclone given by Bullock & Johnson (1972), using the advective method, may be too low by a factor of two. If allowance for this is made, then the significance of the generation of available potential energy by sensible heating in their hemispheric cyclone will be comparable to Gall & Johnson's (1971) result for a northern hemispheric cyclone, where the bulk aerodynamic method was used.

4. Conclusions

Relative to the estimates from the bulk aerodynamic method, the advective method for estimating the sensible heat flux from the ocean to the atmosphere, devised by Bullock & Johnson (1972) for use in regions with little data, underestimated both the total sensible heat flux into the area of extratropical cyclone and the generation of available potential energy by this flux. The area average from the advective method was approximately 30% less during the first time period and 50% less during the second time period. The spatial distribution of the heat flux and the location of the maximum given by both methods are in approximate agreement, suggesting that the advective method can be used in sparse data regions. The relative differences between the two methods are no greater than the relative differences between estimates for the bulk aerodynamic method where the dependency of the drag coefficient and ten-meter wind speed are varied (Gall & Johnson, 1971).

It is not possible to state with certainty any conclusions on the absolute accuracy of the method. The most likely uncertainties in the advective method stem primarily from the use of the surface geostrophic wind to estimate the surface-layer average wind and from the analysis of the height of the top of the mixed layer. Possibly, comparative diagnostic studies of heat flux in a carefully designed numerical-simulation experiment might establish absolute accuracy for the advective method.

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6. Appendix

List of symbols

g	gravity
R	gas constant for dry air
c_p	specific heat at constant pressure
κ	R/c_p
P_0	surface pressure
P_{00}	1000 mb
P_t	pressure at the top of the mixed layer
θ_0	potential temperature of the air at anemometer height z
θ_s	sea surface temperature
ρ	density of the air
U_{g0}	the surface geostrophic wind vector
$U_{g\eta}$	geostrophic wind component parallel to the sea-surface temperature gradient
η	denotes a direction parallel to the sea-surface temperature gradient
$U(z)$	wind speed at anemometer height z
$C_a(z)$	aerodynamic drag coefficient at anemometer height z
F_0	the sensible heat flux across the air-sea interface

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СРАВНЕНИЕ ДВУХ МЕТОДОВ ОЦЕНКИ ПОТОКОВ ТЕПЛА В ОКЕАНИЧЕСКИХ ВНЕТРОПИЧЕСКИХ СИСТЕМАХ СИНОПТИЧЕСКОГО МАСШТАБА

Адвективный метод оценки потока тепла из океана в атмосферу, разработанный Баллоком и Джонсоном (1972) для использования в океанических областях с малым количеством данных, сравнивается с аэродинамическим методом. Результаты расчётов для конкретного случая над Северной Атлантикой показывают, что метод Баллока и Джонсона даёт пространственные распределения потоков, аналогичные полученным аэродинамическим методом, но недооценивает величину потоков тепла.