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The summer distribution of coastal minke whales (*Balaenoptera acutorostrata*) in the southern outer Moray Firth, NE Scotland, in relation to co-occurring mesoscale oceanographic features

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ABSTRACT

Data on the distribution of northern minke whales (*Balaenoptera acutorostrata*) in the coastal waters of the southern outer Moray Firth in northeast Scotland were collected from May to October, 2000 to 2004 inclusive. During this period, 127 encounters with *B. acutorostrata* were recorded during systematic boat-based surveys. The encounters were subsequently converted to number of animals sighted per unit of survey effort (SPUE) for comparison with mesoscale oceanographic features. Using Advanced Very High Resolution Radiometer (AVHRR) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) imagery, monthly composite images of sea surface temperature (SST) and chlorophyll-*a* concentration (Chl-a) were obtained. In the SST imagery two oceanographic features appeared to dominate the Moray Firth region: a cold water current and a warm water plume. The results show that the SPUE of *B. acutorostrata* was significantly higher during warm plume events than when the cold current was dominant (Mann–Whitney U, $P=0.0167$). Levels of phytoplankton biomass also appeared to be substantially greater during warm water plume events. In conclusion, it is hypothesised that those areas of highest minke SPUE are directly related to the presence of targeted prey attracted by high densities of phytoplankton. Although these whales were found to occur across the survey area, throughout the study period, their distribution is concluded to be highly dependent upon the presence of co-occurring mesoscale features. These, as well as other physiographic environmental determinants, are all thought to be important in forming this heterogeneous coastal ecosystem.

1. Introduction

Understanding the way in which cetaceans interact with the surrounding environment has now becoming a key tool in not only their subsequent conservation but in the management of the ecosystems of which they form part. Due to their high trophic status and vulnerability to anthropogenic effects marine mammals, such as cetaceans, are ideally suited to act as indicator species of ecosystem change (Hooker & Gerber, 2004). Therefore, many marine protected areas (MPAs) are centred on the conservation of marine mammals. In the marine environment the factors which dictate the distribution of many marine species, including cetaceans, are often highly variable spatially and temporally (Forney, 2000). Currently the boundaries or extents of already established marine protected areas are either chosen arbitrarily with concern to the environment, i.e. being based solely on high sighting frequencies (Hamazaki, 2002) or with respect to those features of habitats which do not change or vary at extremely low rates. These features are commonly referred to as fixed or stationary environmental (a.k.a. eco-geographical) variables (EVs) and examples include bathymetric characteristics and sediment class types (Naud et al., 2003; Yen et al., 2004). An intrinsic feature and problem of marine protected areas or reserves established using either of the procedures above is that their boundaries become permanently fixed (Hamazaki, 2002). However, as stated previously, cetacean distributions may change, i.e. shift within or outside designated protective zones, due to oceanographic changes of non-fixed environmental parameters (e.g. sea surface temperature, salinity, productivity).

It has been shown that correlations exist between cetacean distributions and non-stationary ocean features, such as fronts and eddies (Kimura et al., 1997; Yen et al., 2004). It is believed that though these features may affect cetacean distribution directly, e.g. energy budgets and thermoregulation (Hind & Gurney, 1997), it is more probable that they affect cetaceans secondarily, through effects on the distribution of prey (Davis et al., 2002). These features act to aggregate weakly swimming organisms (e.g. plankton) and bring them closer to the surface, allowing greater access to predators (Croll et al., 1998). This process by which oceanographic features occur has been important in understanding the presence and changes of top marine

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predator distribution within certain areas (Yen et al., 2004). Examples of non-stationary cetacean habitats include common dolphin (*Delphinus delphis*) associations with a frontal system located between the Celtic and Irish Seas, known as the Celtic Sea front (Goold, 1998). Also, sperm whales (*Physeter macrocephalus*) have been found to be associated with warm core ring formation in the North Atlantic (Griffin, 1999).

The northern minke whale *Balaenoptera acutorostrata* Lacepede 1804 is the smallest and most abundant of the mysticete or baleen whales in UK waters (Reid et al., 2003). Sightings of *B. acutorostrata* have been recorded in the Moray Firth, the largest embayment of its kind in the North East of Scotland (Robinson et al., 2004). However, little focused research has been conducted on the presence of this cetacean species in this area in relation to underlying environmental factors. The Moray Firth is a large triangular embayment, bounded on two sides by land and covers an area of approximately 5230 km^2 (Eleftheriou et al., 2004). It is the largest of its kind on the east coast of Scotland and contains within it three smaller Firths, the Dornoch Firth, Cromarty Firth and Inverness Firth. The Moray Firth is classed as an 'open system' and forms an integral part of the wider North Sea basin and Atlantic beyond, sharing large scale environmental factors such as water circulation and climate patterns (Wright et al., 1998, Eleftheriou et al., 2004). It is a recognised area of outstanding biological importance (SNH, 2006), the inner section designated as a Special Area of Conservation (SAC).

The aim of present study is to investigate and ascertain if any significant patterns can be seen between the distributions of *B. acutorostrata* and mesoscale oceanographic features (e.g. frontal boundaries and eddies) which are present in the southern outer part of the Moray Firth. The findings of the study can then be used to reconsider the current conservation and management status of this species in the Moray Firth.

2. Methods

All data used in the present study were collected during the months of May to September, 2000–2004, from an 880 km^2 area within the southern outer Moray Firth, north east Scotland (Fig. 1). The area was divided into four routes including three dedicated minke whale routes (inner, middle and outer) and a coastal survey route also used to locate co-occurring bottlenose dolphins. These were divided into a further four sub routes. Surveys consisted of travelling between way points along each route. All surveys were conducted using an Avon Searider ridged inflatable boat (RIB). Vessel was propelled by a 90 hp two-stroke outboard engine and fitted with a Lowrance GPS unit, sonar and thermistor probe. Surveys were conducted at a speed of 10–18 km per hour with a crew of between 3 to 7 observers. Surveys were also carried out at sea states of 3 or less (Beaufort Scale) in good light conditions. If the sea state increased beyond 3, or the weather deteriorated, the survey was either halted temporarily until conditions improved or was terminated. To assist observations a pair of reticulated 7×50 122 mm waterproof compass binoculars were used whilst on surveys. When animals were sighted, the time and GPS position of the animals were recorded. In addition environmental data were collected including sea state and weather conditions.

The sightings frequency (number of whales sighted) of *B. acutorostrata* was calculated for each month surveyed. The total amount of effort (minutes spent on effort surveying) was also calculated for each month surveyed. To correct for biases, generated by different quantities of *B. acutorostrata* observed in different months because of differing effort spent surveying, the sighting per unit effort (SPUE) was then calculated using the following equation:

$$E_i = \frac{n}{t_{\mathrm{T}}}$$

Where

E_i Sightings per unit effort (SPUE)
n Total number of sightings
t_{T} Total amount of effort (minutes).

Satellite imagery was used to compare *B. acutorostrata* encounter distributions with oceanographic features in the Moray Firth embayment. Sea surface temperature (SST) data were obtained from Advanced Very High Resolution Radiometer (AVHRR) monthly composite images of the Moray Firth, 2001–2004, May–October,

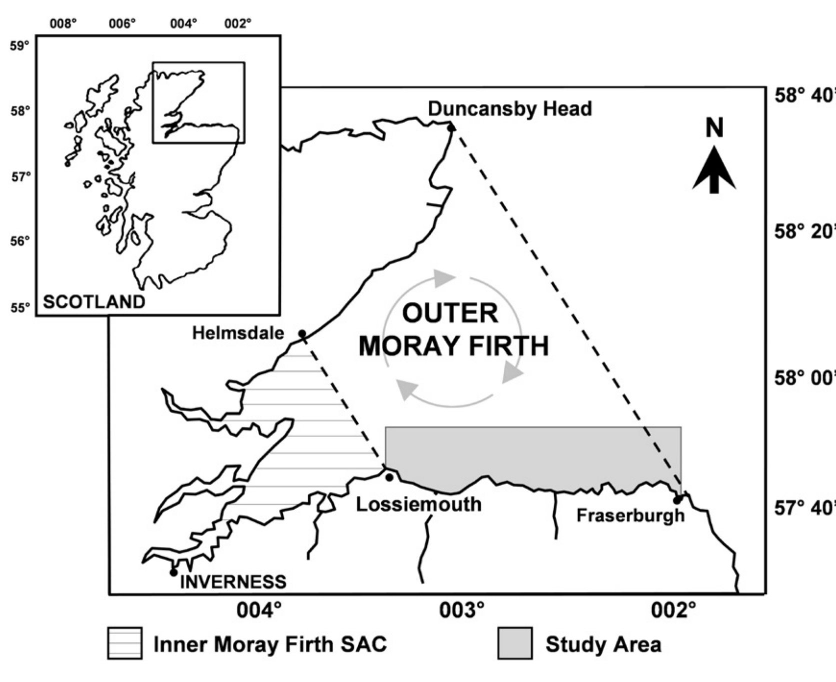

Fig. 1. Map of the Moray Firth in northeast Scotland. The arrows indicate the direction of the Dooley Current. The Special Area of Conservation is also highlighted by the shaded area, and the 880 km2 study area is shown.

supplied by the NERC Remote Sensing Data Analysis Service (RSDAS). Images supplied by RSDAS were atmospherically corrected and provided in a Mercator projection. Values or Digital Numbers (DN) associated with each pixel of the AVHRR images supplied were converted into real SST (°C) values using the following equation as supplied by RSDAS:

$$SST = DN \times 0.1 - 0.3$$

Where

SST Sea Surface Temperature (°C)
DN Digital number or the value of each pixel.

Chlorophyll-*a* (Chl-a) concentration data were obtained from the Sea-viewing Wide Field-of-view sensor (SeaWiFS) monthly composite images of the Moray Firth, 2001–2004, May–October, also supplied by RSDAS. Images supplied by RSDAS were atmospherically corrected and provided in a Mercator projection. Values or Digital Numbers (DN) associated with each pixel of the SeaWiFS images supplied were converted into real Chl-a (μg l^{-1}) using the following equation:

$$CHL = 10\hat{}[DN \times 0.015 - 2.0]$$

Where

CHL Chlorophyll-*a* (μg l^{-1})
DN Digital number or the value of each pixel.

Images were subsetted and manipulated to best show the presence of ocean features using ERDAS Imagine © image processing software.

Mann–Whitney *U* non-parametric analysis of variance tests was used to determine whether there were any significant difference in minke whale encounter frequency observed between different dominating oceanographic feature events occurring in the Moray Firth in this period.

3. Results

During the research surveys 127 *B. acutorostrata* were encountered. There appeared to be high variability in SPUE between the different months surveyed (Table 1). From the remote sensing monthly composite images SST varied considerably both temporally between months and spatially across the Moray Firth. Two oceanographic mesoscale features were observed to dominate the Moray Firth; a current of cold water extending across the mouth of the embayment, and circulating clockwise into and around the Moray Firth (for example, the AVHRR and SeaWiFS monthly image composite from June 2001 shown in Fig. 2A), and a plume of warm water was observed extending out from the inner Moray Firth into the wider embayment and North Sea beyond (for example, the AVHRR and SeaWiFS monthly image composite from September 2001 shown in Fig. 2B). The lowest temperatures observed were approximately 10 °C during cold current events, whilst during warm plume events SST values reached a maximum of 15 °C. Corresponding images of chlorophyll-*a* concentration also showed considerable variation both temporally and spatially across the Moray Firth. The amount of potential phytoplankton biomass present appeared to be substantially greater, particularly within the study area, during warm plume events (mean Chl-a = 1.2 μg l^{-1}) than times of cold current dominance (mean Chl-a = 0.5 μg l^{-1}).

Table 1
Sightings per unit effort (SPUE) of minke whales (*B. acutorostrata*) encountered during the study for the months May to September between 2000 and 2004

Year	Month				
	May	June	July	August	September
2000	0.0000	0.0000	0.0000	0.0000	0.0192
2001	0.0000	0.0093	0.0365	0.0367	0.0183
2002	0.0000	0.0000	0.0000	0.0067	0.0270
2003	0.0000	0.0013	0.0379	0.0162	0.0189
2004	0.0000	0.0000	0.0000	0.0000	0.0000

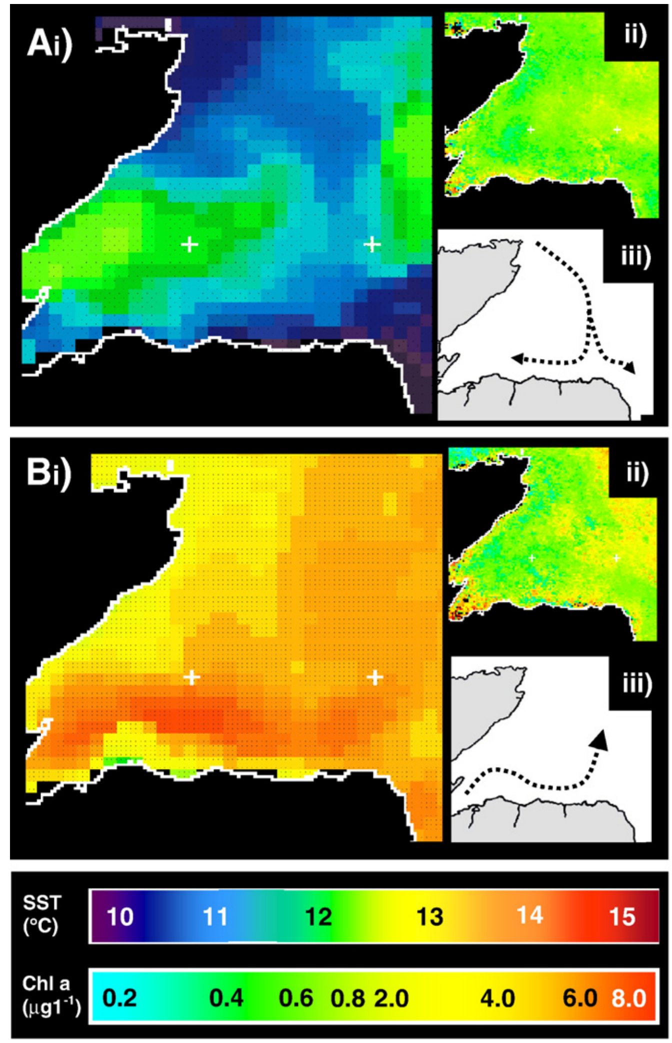

Fig. 2. Selected images showing the presence and interactions of two oceanographic features identified in the Moray Firth. A i) AVHRR monthly composite image of SST, June 2001 ii) SeaWiFS monthly composite image, Chl-a concentration, June 2001 iii) illustration depicting the location and direction of the cold water current. B i) AVHRR monthly composite image of SST, September 2001 ii) SeaWiFS monthly composite image, Chl-a concentration, September 2001 iii) illustration depicting the location and direction of the warm water plume.

Spearman's Rank Coefficients were calculated to determine the presence of significant correlations between the SPUE of minke whales encountered and the period in which surveys were conducted (see Fig. 3). There was a significant correlation between the minke whale SPUE and month encountered ($S = 0.470$ $P = 0.018$). However, no significant correlation between the minke whale SPUE and year encountered ($S = -0.141$ $P = 0.501$). Therefore it was assumed that factors affecting changes in minke whale SPUE were more significant across monthly scales within years rather than between the years themselves. Therefore, in relation to the changes in occurrence of the two mesoscale feature identified above, percentage occurrence for each feature was calculated for both across year and month (see Fig. 4). Bar charts of percentage occurrence appear to indicate across years that little variation between oceanographic mesoscale features. However, there appears to be a high level variation in mesoscale feature percentage occurrence across the different months observed.

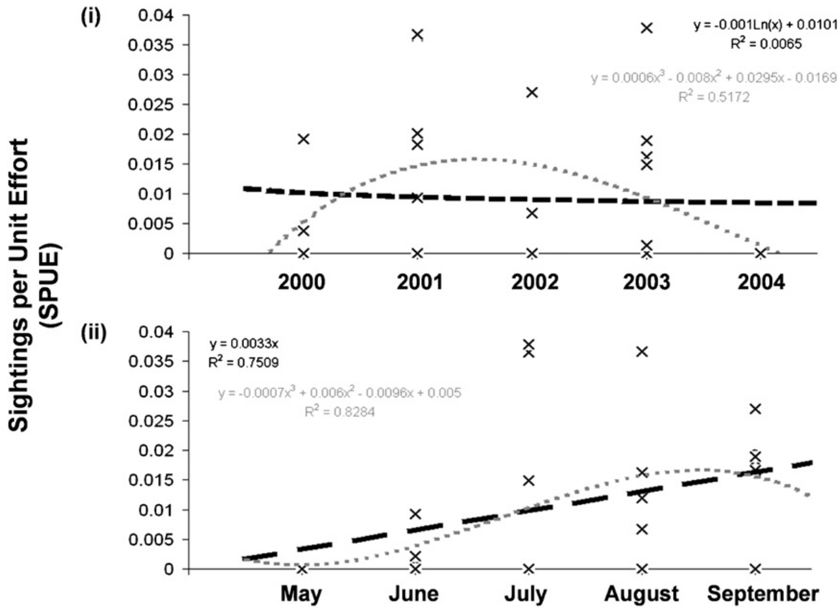

Fig. 3. Scatter plots showing the presence of correlations occurring between minke whale SPUE and (i) year and (ii) month in which whales were encountered. Each plot includes straight line (black) and 2nd order polynomial (grey) trendlines, line equations and values for *R*.

Therefore it is assumed that variation in the occurrence of mesoscale features was more significant across monthly scales within years rather than between the years observed.

The observations of monthly minke whale SPUE were divided into times when the cold water current or warm water plume was in dominance; plume dominance was defined as when the plume extends out of the mouth of the Moray Firth, breaking through the cold current; current dominance was defined as when current stretches across the mouth of the Moray Firth, unbroken by the warm plume. Of the monthly composites (2001–2004) analysed it was found that the cold current dominated the embayment for six months whilst the warm plume was in dominance for ten months. No dominance rating could be made for the remaining four months because of low quality images due to small sample sizes of individual

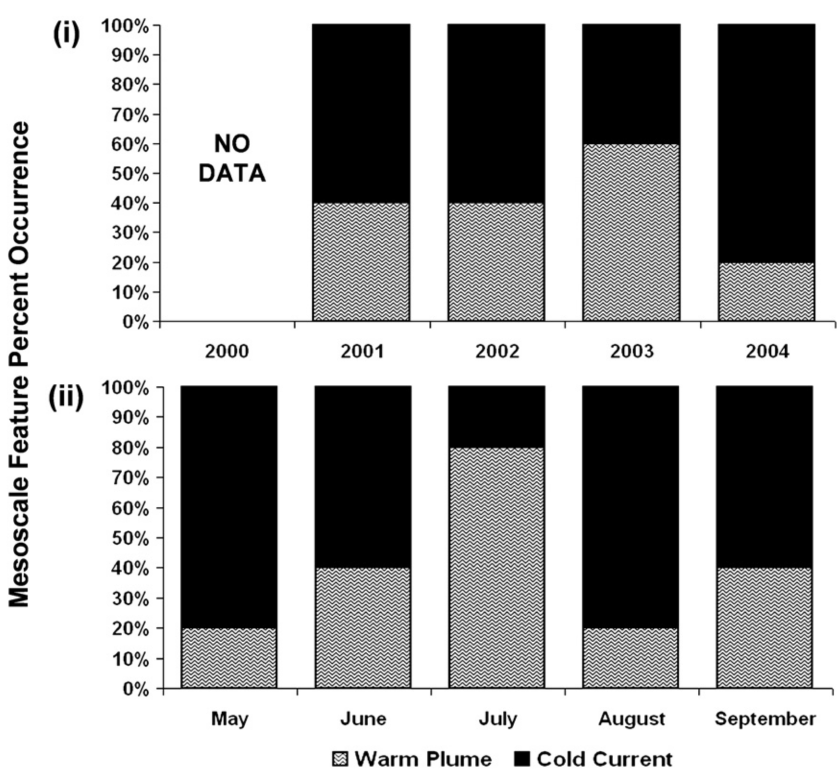

Fig. 4. Bar charts showing the percentage occurrence of the two mesoscale features (warm plume, cold current) observed to dominate the Moray Firth area across the different (i) year and (ii) month in which data were available.

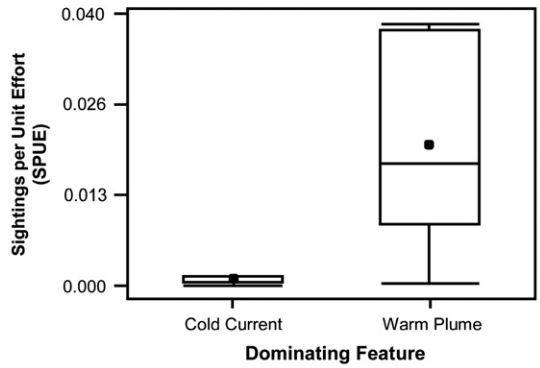

Fig. 5. Box plot showing differences in *B. acutorostrata* sightings per unit effort (SPUE) between months when either the cold water current or warm water plume was in dominance. A Mann–Whitney *U* test showed there was a significant difference in encounter frequency between these two periods (W=24.5 P=0.0167). The mean, interquartile range and range are shown.

images available to construct the composites of those months. It was found that minke whale monthly SPUE was significantly different between warm plume and cold current events observed during the study period (W=24.5 P=0.0167) (Fig. 5).

4. Discussion

Findings of the study show that there appears to be a correlation between the presence of northern minke whales and the occurrence of two mesoscale oceanographic features observed in the Moray Firth. These features are identified as the Dooley Current (Eleftheriou et al., 2004) which transports cold water south from the north Atlantic, into the northern North Sea, then circulating it clockwise into and around the Moray Firth. The plume feature is considered to be due to the warming of water within the shallow inner part of the firth. This is then transported out into the wider embayment and North Sea by the outflow from the many smaller firths and rivers which discharge into the Moray Firth, which is in turn fed further by runoff and snowmelt from the surrounding Scottish highlands. It is, however, thought that although whales could be affected directly by these forces (e.g. energy budgets and thermoregulation) it is more likely that these forces are affecting the abundance of minke whale prey. From stomach content analysis studies of stranded animals, it was found that the primary constituent (70%) of the diet of minke whales occurring around Scotland, including the Moray Firth, was the sandeel *Ammodytes sp.* (Pierce et al., 2004). The availability of sandeels to minke whales is highly dependent upon the presence of phytoplankton prey to draw them out of the benthic sediments in which they bury themselves for protection (Wright et al., 2000; Macleod et al., 2004). From the images of chlorophyll-*a* concentration, when the plume feature was in dominance, primary productivity levels appear greater than at times of cold current dominance. Therefore, it is hypothesised that the minke whales may only choose or show preference to forage in areas at times when prey is most available. It is therefore hypothesised that, within the Moray Firth system, this predominantly occurs when the warmer waters of the plume feature stimulate greater phytoplankton biomass and associated higher primary productivity, further increasing the availability of sandeels for foraging minke whales.

Previous studies have attempted to show correlations between the distributions of *B. acutorostrata* and oceanographic features. However, due to problems of low sample size of data, few significant patterns or correlations have been observed. Kasamatsu et al. (2002) managed to show strong correlations between the presence Antarctic minke whales (*B. bonaerensis*) and ice edges areas in the Bellinghausen and Amundsen Seas in the Antarctic. Although no significant correlations were found between minke whale density and sea surface temperature, it was observed that densities appeared to be higher during the surveys conducted during 1982/1983 when the region was experiencing intrusions of colder water (Kasamatsu et al., 2002). In the current study it appears that although minke whales occur within this area their distribution within it may be highly, if not totally, dependent on a suite of co-occurring environmental features and variables. Further efforts need to be focused on how these dynamic coastal communities are structured and affected by the shifting occurrence of mesoscale features, such as cold currents and warm plumes. Also, minke whales and trophically similar cetacean species may provide perfect bio-monitors and bio-indicators, indicating the effects these features may have on coastal ecosystem structure due to their ability to react quickly to shifts in optimal prey abundance (Littaye et al., 2004). In understanding these relationships changes can be made to future MPA's designed for these species of marine mammal, compensating for spatial and temporal shifts in their distribution due to the effects of mesoscale features and co-occurring prey species. Further understanding how these marine ecosystems function will also help to predict how, with the effects of climate change, these communities may alter, especially in the distribution of cetaceans and their prey, an example of which would be the minke whale and sandeel.

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