Sea level is not level:

the case for a new approach to predicting UK sea-level rise

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and Antony Long

ABSTRACT: Current predictions for future sea-level rise along the UK coasts are based on IPCC values for global mean sea-level change combined with information on land movements, changes in tidal range and storm surges. In this article we argue that the global IPCC sea-level values should be replaced by a suite of regional values, to take into account known processes that cause regional changes in sea-surface topography. Quantification of these processes, which include gravitational adjustments of the ocean surface and nearshore ocean-density changes, requires the use of numerical ocean and geophysical models. 'Ocean siphoning' and 'continental levering' are two additional mechanisms that are not included in IPCC assessments, but can be quantified using a modelling approach. Data of vertical land movements based on geological information alone, as presently used by UKCIP (Defra) in UK sea-level rise scenarios, are potentially unreliable as they represent, in essence, values of relative land-level (or sea-level) change. These data can be improved by including geophysical model predictions and GPS measurements in assessments of vertical land motion. A combined modelling/geological approach will produce more robust regional sea-level predictions for the UK that are of real practical value to agencies responsible for coastal defence and flood protection.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) released its Fourth Assessment Report in 2007 (IPCC, 2007). The report contains predictions for global sea-level rise ranging from 0.18m to 0.59m by the year 2100 AD (Figure 1). The wide range of these predictions reflects the various greenhouse gas 'emission scenarios' that may occur this century, each depending on factors such as population growth, industrial development, and efforts to curb greenhouse gas pollution. These sea-level predictions are presented as *global averages*, so it is justified to raise the question 'How useful are these predictions in practice?' Take, for example, the case of a council of a coastal town in the United Kingdom that wants to ascertain whether or not their coastal defences are up to scratch for the next 100 years. The latest IPCC report includes a separate chapter on regional changes in future climate, with seven pages devoted to Europe, but, unfortunately, no such regional analysis is made for sea-level changes. The report acknowledges that sea-level rise will be variable depending on location, but does not carry this through into specific regional predictions. How useful, then, are the IPCC numbers on a local or regional scale?

In trying to provide an answer to this question, we need to understand that several factors will influence future sea-level change at the local to regional scale: a change in local mean sea level, a change in tidal range, changes in storm-surge heights and vertical land movements. The IPCC predictions only address the first of these four terms – changes in mean sea level – and only in a simplistic manner and at a global level. They do not take into account any of the other processes. It is left in the hands of national agencies to try and translate the global IPCC predictions into usable numbers for specific coastal locations. In the UK this agency is the United Kingdom Climate Impact Programme (UKCIP), a subsidiary of the Department for Environment, Food and Rural Affairs (Defra). We will highlight their current sea-level predictions towards the end of this article.

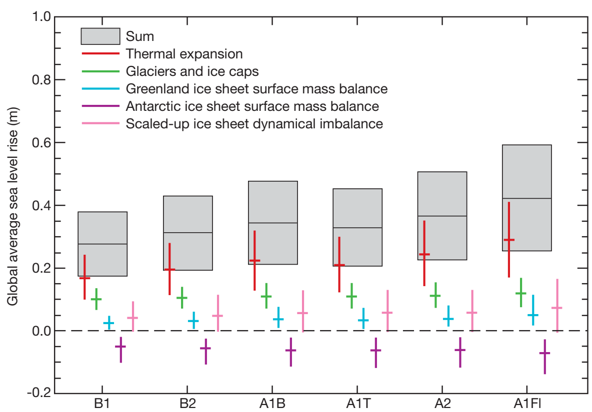

Figure 1: *IPCC (2007) predictions of global mean sea level for the last decade of the twenty-first century, relative to 1980-1999. The different predictions refer to different scenarios; higher sea-level rise is predicted from scenarios that include rapid population and economic growth, and growth in greenhouse gasses. After IPCC, 2007.*

First, though, we will outline the various processes that contribute to local sea-level changes and that should be taken into account in future predictions. What we argue is that sea level is in fact far from 'level' and that future changes in sea level will vary widely from any assumed global value. Unfortunately, many of the processes responsible for such variability are essentially ignored by the IPCC, and by the many agencies involved in predicting local- to regional-scale sea-level rise scenarios. The good news, though, is that sea-level scientists are now developing tools capable of making meaningful predictions that take into account these hitherto ignored processes.

Changes in global and local mean sea level

For the twentieth century, the average global rate of sea-level rise was 1.7mm/yr, but satellites measured the significantly higher rate of 3.1mm/yr for the period 1993-2003 (Cazenave and Nerem, 2004; Church and White, 2006; Holgate, 2007). Ten-year periods with similar or even higher rates of rapid sea-level rise have occurred within the twentieth century. For example, the decade 1975-1985 experienced a rate of 5.3mm/yr (Holgate, 2007). It is therefore not yet known whether the recent acceleration of sea-level rise represents a change in the long-term trend (IPCC, 2007). However, in the future, further changes in global mean sea level will occur, due, in about equal proportions, to melting of land-based ice (the polar ice sheets of Antarctica and Greenland, other ice caps and mountain glaciers) and thermal expansion of the sea, primarily in the upper layers of the oceans. We now look in detail at some of the 'unknowns' which make it difficult to put exact numbers on these global sea-level rise estimates and why single global values cannot be simply translated to a particular coastline.

The 'key uncertainty' identified by the IPCC is that the record of global sea-level rise since 1961 appears to have been larger than the sums of the known contributions from ice melt and thermal expansion. In other words, it is not known where all of the sea-level rise has come from (Munk, 2002). This in itself raises an interesting conundrum: how can we expect to predict future sea-level changes accurately if we do not even know the sources of sea-level rise in the recent past? Fortunately, the sources of sea-level rise are better known for the period since 1993, when the first satellites started to measure sea-level changes on a global scale from space. But before the 1990s, measurements relied entirely on tide gauges which only record changes of sea level along coasts and not the open oceans which cover the majority of the world. It is therefore possible that the 'missing' sea-level rise is simply a consequence of the methods of measurements used before the arrival of satellite technology. On the other hand, it is also possible that a hitherto unknown source has contributed to global sea-level rise during this period. One possible source is the polar ice sheets which may have experienced episodes of rapid melt in the earlier part of the twentieth century, before monitoring of them began (Miller and Douglas, 2004). Some of the 'missing' sea-level rise may well have been released during such events.

Another complicating factor is that the globally predicted mean sea-level changes will, for most coastal locations, be different from any local change in mean sea level. The reason for this is that the sea surface is not level, and its surface topography is continually changing. Measured relative to the centre of the earth, the global sea surface varies in altitude by over 100m, mostly reflecting variations in the density of rocks that underlie the oceans (this is known as the 'geoid'). The sea-surface topography at long wavelengths is dynamic and adjusts to regional variations in the gravity field of the Earth. Over time-scales in the order of centuries the shape of the geoid is fairly constant but, interestingly, the gravity changes caused by any fluctuation in ice-sheet mass can deform the sea-surface topography on shorter time-scales. These are of considerable relevance to future sea-level rise predictions. Geophysicists, who have known about this effect since the late 1800s, have calculated that sea-level rise caused by the melting of an ice sheet will not be evenly distributed across the

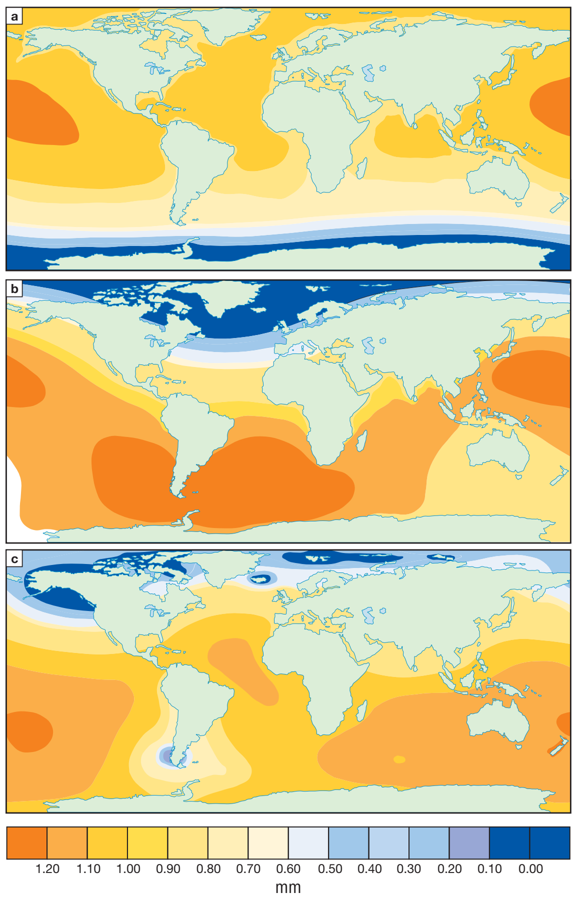

Figure 2: *Model predictions of how 1mm of water equivalent ice melt would be redistributed across the world's oceans were that water to come from the melting of (a) Antarctica, (b) Greenland or (c) the small valley glaciers and ice caps. After Mitrovica* et al., *2001.*

globe. So, the volume of water in the oceans increases if a polar ice sheet melts, but at the same time, the strength of the gravity pull from the ice sheet on the oceans falls. The overall result of these processes is that sea-level rise occurs faster in areas distal from the melting source (Figure 2).

Also important on short time-scales are sea-surface topographical changes caused by variations in sea-surface temperature. These temperature changes and, to a lesser degree, salinity changes, produce variations in the density of the upper layers of the ocean that vary through time and space. Direct measurements of ocean temperatures as well as more recent satellite data enable us to determine that the thermal expansion effect has produced about 2mm per year of sea-level rise in the north-west Atlantic Ocean. Thermal 'contraction', on the other hand, has occurred in the western Pacific and is responsible for about 0.5mm/yr of sea-level fall over the same time period (Figure 3). When we average the observations over a shorter timescale, say the past 15 years, the picture is almost reversed; in the north-western Atlantic Ocean sea level has been falling and in the western Pacific sea level has been rising (Ishii *et al.*, 2006). These variations on decadal timescales are produced by natural climatic cycles such as El Niño and the North Atlantic Oscillation which are superimposed on any longer-term trends. The example illustrates how the time window of observations must be taken into account when sea-level predictions are made. Long-term climatic changes and short-term climatic cycles combine to produce regional patterns of ocean-surface changes of considerable complexity.

Despite the acknowledged importance of thermal expansion and contraction to global and regional sea-level change, their measurement is dependent on data collected from the middle of the oceans away from coastlines. Basic laws of physics dictate that changes in thermal expansion and contraction are related to water depth, so if we can measure sea-surface temperature changes in the middle of the ocean we can calculate the ocean-surface change that might result. But how important is thermal expansion for sea-level rise along a coastline where the water depths are shallow, and how does warming or cooling of the water column in the open ocean translate itself across the continental shelves (with all their complex currents and tides) to reach the coast? This is an important oceanographic problem which, to our knowledge, remains unresolved.

There are other processes that are rarely discussed in relation to future sea-level rise predictions. Ocean basins, for example, are slowly increasing in size as the Earth's shape adjusts to the redistribution of mass from the land to the oceans which accompanied the melting of the ice sheets during the last 20,000 years or so (Figure 4A). During the last ice age, the load of the northern hemisphere ice sheets depressed the Earth's surface beneath the ice itself, and created an area of uplift around the ice-sheet margins. This zone of uplift is known as a 'forebulge'. As the ice melted, however, the load of the former ice sheet was removed and the Earth's crust responded by uplifting, a process that continues to the present day. Moreover, the former 'forebulge', once located on the periphery of the ice sheet, is now collapsing and sinking. Where the sinking forebulge is part of the sea floor, it creates space for water to flow into. Geophysicists have named this effect 'ocean siphoning' because it is associated with ocean water flowing from the equatorial and low latitude regions of the oceans, which lie beyond the former ice limits, to higher latitudes that were formerly glaciated (Mitrovica and Peltier, 1991). However, other processes serve to increase the size of the oceans in the equatorial regions too (Figure 4B). Here, the increasing water load

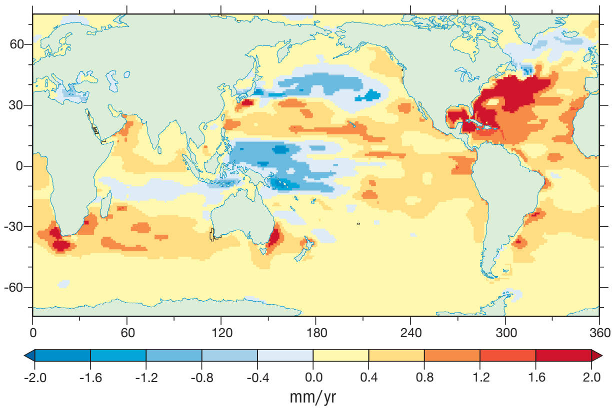

Figure 3: *Global sea-level changes due to thermal expansion recorded since 1955. After Ishii* et al.*, 2006; IPCC, 2007.*

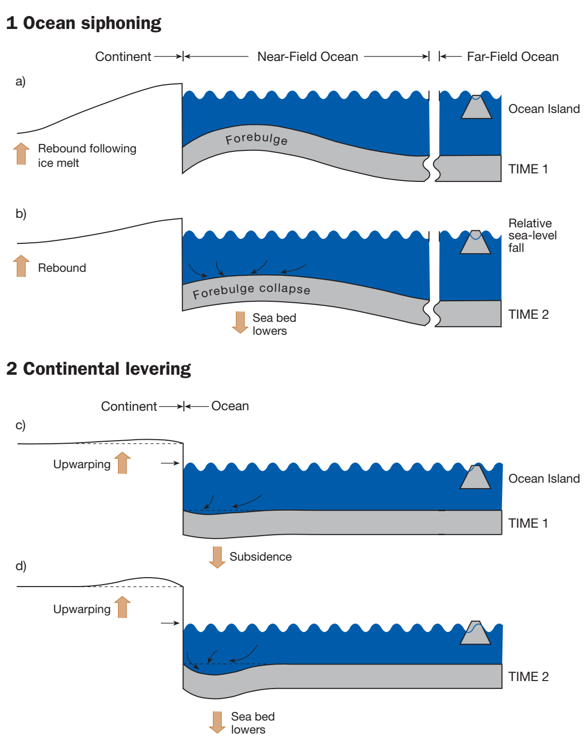

Figure 4: *Processes that influence the redistribution of water associated with Earth loading and unloading by ice and water; (1) 'ocean siphoning', in which water flows from the equator towards the collapsing forebulges of the mid and high latitudes, (2) 'continental levering', whereby water loading of the continental shelf causes rebound of the coast. After Mitrovica and Milne, 2002.*

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that results from ice melt depresses the continental shelves and lifts the adjacent continents – hence the term 'continental levering' is used to describe this process. Together, 'ocean siphoning' and 'continental levering' are responsible for a global sea-level fall of about 0.3mm per year (Mitrovica and Milne, 2002). This overall fall will partly offset, albeit by a small amount, any rise in future sea level caused by melting of land-based ice and by thermal expansion of the oceans.

This overview should make it clear that a single figure for global sea-level rise, as produced by the IPCC, means little. In reality, the IPCC estimates should be labelled as 'changes in global ocean volume', not 'mean sea level', which is a term that can easily be misinterpreted. Clearly, regional predictions are required to take into account spatial variations produced by gravitational and steric effects. Along some coastlines these effects will result in sea-level rise that is greater than the global average, especially in the middle latitudes where the gravitational effects of polar ice melt are greatest. If ocean waters are warming near these coastlines, the sea-level rise will be even more pronounced. In coastal areas at high latitudes and near the equator, gravitational changes will produce sea-level rise that will be less than the global average. This could be offset by thermal expansion, but, if ocean waters are not warming up by much, the total sea-level rise could be considerably less than the global average.

Changes in tidal range

Coastal storms and hurricanes illustrate the fact that, in practical terms, the high (or extreme) water level, rather than mean sea level, controls the short-term impact of sea-level rise on any given coastline. Possible changes in tidal range are therefore an important factor to take into account because as tidal range changes so too will the height and impact of storm waves. Tidal range is sensitive to sea-bed bathymetry, so once a regional change in mean sea level is computed, numerical models that contain an accurate description of offshore bathymetry can determine whether the tidal wave will change its shape with future sea-level rise. A steepening tidal wave, for example, could be produced in a coastal setting that is changing towards a more funnel-shape configuration (e.g. by land reclamation). Deeper water could also produce a decrease in frictional effects, which would increase the heights of the high tides. There are also situations in which the tidal range will decrease with a rise of sea level so that the rise of mean sea level will to some extent be balanced by a lowering of the high water level during high tide.

Changes in storm surges

The highest water levels are produced during storms. Unfortunately, when sea level rises, the probability that a given water level will be exceeded increases exponentially – this is the essence of why sea-level rise is a societal concern. Moreover, most climate models predict an increase in the severity and frequency of storms in north-west Europe (Lowe and Gregory, 2005). These predictions also consider changes in wind direction because a coastline could become more sheltered or more exposed with changing wind patterns. This is despite the fact that changes in extreme water levels, unrelated to those of mean sea level, are not apparent from sea-level measurements in past decades (Woodworth, 2006).

Vertical land motion

The Earth's crust is constantly moving, adjusting to changes in stresses in the Earth's interior as a result of a wide range of tectonic and other processes. As we have seen already, the effects of ice loading and unloading persist to the present day, influencing patterns of land and sea-floor uplift and subsidence. The rates of change due to these and other processes that influence vertical land motion, such as sediment shrinkage due to dewatering, may equal or significantly exceed the changes in global average mean sea-level. They must, therefore, be taken into account when considering future local to regional sea-level predictions.

The UK Climate Impact Programme (UKCIP) is the government agency responsible for translating global IPCC predictions to the specifics of the UK coastline. Their methodology entails combining IPCC sea-level rise predictions to 2080 with a value for land uplift or subsidence. They do not address any of the other factors described here. It should be clear from the discussion above that the IPCC values can, at best, only serve as a very rough approximation at the regional scale. What about the figures used by UKCIP for UK vertical land motions?

The importance of vertical land movements is quite noticeable in the UKCIP sea-level rise predictions (Table 1). They are higher in southern Britain than in Scotland. Relative land uplift is occurring in Scotland where rebound is still taking place after the melting of

Table 1: *Estimates of UK sea-level rise by Defra to AD 2115 based on estimates provided by UKCIP (www.defra.gov.uk/environ/fcd/pubs/pagn/climatechangeupdate.pdf).*

Administrative or devolved region	Assumed vertical land movement (mm per year)	Net sea-level rise (mm per year) 1990-2025	Net sea-level rise (mm per year) 2025-2055	Net sea-level rise (mm per year) 2055-2085	Net sea-level rise (mm per year) 2085-2115
East of England, East Midlands, London, SE England	-0.8	4.0	8.5	12.0	15.0
South West and Wales	-0.5	3.5	8.0	11.5	14.5
NW England, NE England, Scotland	0.8	2.5	7.0	10.0	13.0

the relatively small British and the much larger Fennoscandinavian ice sheets. The coastlines of southern Britain, which were outside the limits of former glaciations, are slowly sinking due to the shrinking of the former forebulge associated with these ice sheets. This exacerbates the effects of any future sea-level rise.

Vertical land-motion data used by UKCIP are taken from a paper by Shennan and Horton (2002) who calculated the rate of *relative* sea-level changes around Britain during the past 4000 years from a large database of radiocarbon-dated samples (mostly coastal peat) which were formed very near contemporaneous sea level. *Relative* sea level describes the changing height of the sea with respect to the land – the term includes both land and sea-level variations. Therefore, it is not possible to use this database on its own to distinguish between land-level changes and sea-level changes. By equating the *relative* values published by Shennan and Horton (2002) to *absolute* values of land motion, UKCIP makes the assumption that global sea-level rise during the past 4000 years has been zero and that no other factors, apart from land movement, have produced the change in relative sea level. We have already discussed the question of regional sea-level variability, which undoubtedly has operated in the past. In addition to this, the question of whether there has been any meltwater addition to the world's oceans during the past 4000 years is still unresolved, and differences of opinion on this subject are prevalent in the literature (e.g. Lambeck, 1997; Peltier, 2002; Milne *et al*., 2005). Any global sea-level rise during the past 4000 years would lower the UKCIP estimates of land motion. For example, the 18cm of global sea-level rise that has occurred in the past century (Church and White, 2006) would reduce the values by about 0.1mm/yr.

Where do we go from here?

It is quite easy to criticise existing sea-level rise predictions, but offering a useable alternative is an entirely different proposition. There remain many gaps in the knowledge of sea-level changes, some of which, such as the contributions of land-water storage associated with irrigation and dam construction, are very difficult to quantify. The main point that we want to put forward in this article is that there are ways in which we can improve sea-level predictions, not only by tackling some of the 'unknowns' in the IPCC projections, but, crucially, by taking into account processes that we do know about but have so far ignored. What are some of the improvements that can be offered today given the expertise, data sets and computer models that are available within the UK sea-level science community?

Twentieth century sea-level changes

A first effort should be to close the budget of sea-level changes during the past century. Before we can adequately predict how much sea-level rise will occur in the next century, it seems pertinent to resolve what the contributing sources have been in the recent past. We have suggested that the missing water in the twentieth century may have been derived from a period of rapid melt from one or both of the Greenland and Antarctic ice sheets. A possible solution is offered by the observation that we described earlier, i.e. that the ocean surface changes its shape depending on the source of ice melt. Using geophysical models, we can compare the observed global pattern of twentieth century sea-level measurements from tide gauges and proxy indicators (such as salt-marsh sediments that can act like sea-level recorders) with the spatial and temporal patterns (or 'fingerprints') predicted by geophysical models that would result from various ice-melt scenarios. This pattern is complicated by steric changes associated with ocean temperature changes, but for the past 50 years measurements of ocean temperature are available and can be used, again taking a modelling approach. Once we have a better understanding of the processes that have produced sea-level changes in the twentieth century, we can use these 'boundary conditions' as starting points to model sea-surface topography and ice-melt scenarios in the future.

Sea-surface topography

The varying topography of the world's oceans due to steric and other oceanographic and atmospheric effects is now well established from satellite measurements. Rather than adopting a 'flat' ocean surface, the IPCC should take into account this dynamic sea-surface topography. Changes in the past 15 years have been observed by satellites and these observations can be used to calibrate ocean models and predict changes in the dynamic sea surface due to future climate change. The same models can be used to calculate how these changes are translated from the middle of the oceans across the continental shelves to reach the coastlines.

Photo: Frank Pearson.

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Scenarios of ice melt

We know that patterns of past and future sea-level change depend on whether the melt source is Greenland, Antarctica, Alaska, Patagonia or any smaller mountain glacier. As explained above, the melting of ice in these areas produces a distinct sea-level 'fingerprint' which can be calculated by geophysical models. These patterns need to be built into a suite of possible ice-melt scenarios which should cover a full spectrum from slow, centennial-scale melting of East Antarctica, to rapid ice-sheet collapse through drawdown of key outlet glaciers in Greenland and West Antarctica.

Vertical land movements

Geophysical models can now separate land-level changes from sea-level changes. A new UK land-motion map needs to be drawn that is based on model estimates of land movements supported by geological data. The geological data should be used to calibrate and validate the models. Surveys by GPS measurements are still quite imprecise but as longer records and improving technology become available, they will surpass the models in their capability to make accurate measurements of land movements.

Conclusion

The prediction of sea-level changes is a complicated affair because global sea level is not level. The sea surface contains considerable topography which is changing through time and which necessitates predictions of sea-level rise on a regional to local scale. The global values offered by the IPCC are of little practical use for coastal planning and they ignore many important sea-level change processes. Current sea-level predictions for the United Kingdom are the sum of IPCC global values and values of vertical land movements. Estimates for both elements are imprecise, but tools are available to make a considerable improvement on both fronts. Geophysical models can be used to predict the pattern of global sea-level change that results from various ice-melt scenarios. They are also capable of calculating vertical land movements. Ocean models can be used to predict how changes in ocean topography will affect coastlines. 'Real' geological and observational data are of crucial importance in this modelling approach. Both types of models should be calibrated by using proxy data and sea-level and ocean-temperature observations made during the twentieth century. As with all climate models, if they can accurately describe and hindcast sea-level changes during the recent past the models will be in a good position to make accurate predictions of sea-level changes for the twenty-first century. The ultimate goal of such a combined modelling/geological approach is to produce sea-level predictions that are of real practical value and usable at a local scale.

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