Direct runoff from the continents supplies about 40,000 km^3/yr of freshwater to the ocean. Runoff is the sum of all upstream sources of water, including continental precipitation, fluxes from lakes and aquifers, seasonal snow melt, and melting of mountain glaciers and ice caps. River discharge also carries a tremendous amount of solid sediments and dissolved nutrients to the continental shelves.

The polar ice sheets of Greenland and Antarctica are the largest reservoirs of freshwater on the planet, holding 7 m and 58 m of the sea-level equivalent, respectively (Vaughan et al., 2013). The net growth or shrinkage of such an ice sheet is a balance between the net accumulation of snow at the surface, the loss from meltwater runoff, and the calving of icebergs and submarine melting at tidewater margins, collectively known as marine ice loss. There is some debate about the relative importance of these in the case of Greenland. Van den Broeke et al. (2009), show the volume transport to the ocean is almost evenly split between runoff of surface meltwater and marine ice loss. In a more recent work, Box and Colgan (2013) estimate marine ice loss at about twice the volume of meltwater (see Figure 5 in that article), with both marine ice loss and particularly runoff increasing rapidly since the late 1990s. According to the Arctic Monitoring and Assessment Programme (AMAP, 2011), the annual mass of freshwater being added at the surface of the Greenland Ice Sheet (the surface mass balance) has decreased since 1990. Model reconstructions suggest a 40% decrease from 350 Gt/y (1970 - 2000) to 200 Gt/y in 2007. Accelerating ice discharge from outlet glaciers since 1995 - 2002 is widespread and has gradually moved further northward along the west coast of Greenland with global warming. According to AMAP (2011), the ice discharge has increased from the pre-1990 value of 300 Gt/y to 400 Gt/y in 2005.

Antarctica's climate is much colder, hence surface meltwater contributions are negligible and mass loss is dominated by submarine melting and ice flow across the grounding line where this ice meets the ocean floor (Rignot and Thomas, 2002). Freshwater fluxes from ice sheets differ from continental river runoff in two important respects. First, large fractions of both Antarctic ice sheets are grounded well below sea level in deep fjords or continental shelf embayments; therefore freshwater is injected not at the surface of the ocean but at several hundred meters water depth. This deep injection of freshwater enhances ocean stratification which, in turn, plays a role in ecosystem structure. Second, unlike rivers, which act as a point source for freshwater)..9(a)d[Tw -sal v

The spatial distributions of these freshwater fluxes drive important patterns in regional and global ocean circulation, which are discussed in Chapter 5.

The Southern Ocean (defined as all ocean area south of 60°S) deserves special mention due to its role in the storage of heat (and carbon) for the entire planet. The Antarctic Circumpolar Current (ACC) connects the three major southern ocean basins (South Atlantic, South Pacific and Indian) and is the largest current by volume in the world. The ACC flows eastward, circling the globe in a clockwise direction as viewed from the South Pole. In addition to providing a lateral connection between the major ocean basins (Atlantic, Indian, Pacific), the Southern Ocean also connects the shallow and deep parts of the ocean through a mechanism known as the meridional overturning circulation (MOC) (Gordon, 1986; Schmitz, 1996, see Figures I-90 and I-91). Because of its capacity to bring deep water closer to the surface, and surface water to depths, the Southern Ocean forms an important pathway in the global transport of heat. Although there is no observational evidence at present, (WG II AR5, 30.3.1, Hoegh-Guldberg, 2014) model studies indicate with a high degree of confidence that the Southern Ocean will become more stratified, weakening the surface-to-bottom connection that is the hallmark of present-day Southern Ocean circulation (WG I AR5 12.7.4.3, Collins et al., 2013). A similar change is anticipated in the Arctic Ocean and subarctic seas (WG I AR5 12.7.4.3, Collins et al., 2013), another region with this type of vertical connection between ocean levels (Wüst, 1928). These changes will result in fresher, warmer surface ocean waters in the polar and subpolar regions (WGII AR5 30.3.1, Hoegh-Guldberg, 2014; WG I AR5 12.7.4.3, Collins et al., 2013), significantly altering their chemistry and ecosystems.

Imbalances in the freshwater cycle manifest themselves as changes in global sea level.

2013) cause regional patterns in sea-level trends which are reflected in the El Niño/Southern Oscillation (ENSO) and the Pacific decadal oscillation (PDO) indices in the Pacific (Merrifield et al., 2012; Zhang and Church, 2012) and northern Australia (White et al., 2014). Interannual changes in global mean sea level relative to the observed trend are largely linked to exchanges of water with the continents due to changes in precipitation patterns associated largely with the ENSO; this includes a drop of 5 mm during 2010-11 and rapid rebound in 2012-13 (Boening et al., 2012; Fasullo et al., 2013).

Some key alterations are anticipated in the hydrological cycle due to global warming and climate change. Changes that have been identified include shifts in the seasonal distribution and amount of precipitation, an increase in extreme precipitation events, changes in the balance between snow and rain, accelerated melting of glacial ice, and of course sea-level rise. Although a global phenomenon, it is the impact of sea-level rise along the world's coastlines that has major societal implications. The impacts of these changes are discussed in the next Section.

Changes in the rates of freshwater exchange between the ocean, atmosphere and continents have additional significant impacts. For example, spatial variations in the distribution of evaporation and precipitation create gradients in salinity and heat that in turn drive ocean circulation;;ptw70(;)3iosi10(,)5(Sf 3(tw)a)-6(t i0.193 5ti)4(f)10(i)4(e) oa 6(phe)13iaswou

Climate Change (IPCC). This report indicates that it is very likely that extreme sea levels have increased globally since the 1970s, mainly as a result of global mean sea-level rise due in part to anthropogenic warming causing ocean thermal expansion and glacier melting (WGI AR5 3.7.5, 3.7.6; WGI AR5 10.4.3). In addition, local sea-level changes are also influenced by several natural factors, such as regional variability in oceanic and atmospheric circulation, subsidence, isostatic adjustment, and coastal erosion, among others; combined with human perturbations by land-use change and coastal development (WGI AR5 5.3.2). A 4°C warming by 2100 (Betts et al., 2011; predicted by the high-end emissions scenario RPC8.5 in WGI AR5 FAQ12.1) leads to a median sea-level rise of nearly 1 m above 1980-1999 levels (Schaeffer et al., 2012).

The vulnerability of human systems to sea-level rise is strongly influenced by economic, social, political, environmental, institutional and cultural factors; such factors in turn will vary significantly in each specific region of the world, making quantification a challenging task (Nicholls et al., 2007; 2009; Mimura, 2013). Three classes of vulnerability are identified: (i) early impacts (low-lying island states, e.g., Kiribati, Maldives, Tuvalu, etc.); (ii) physically and economically vulnerable coastal communities (e.g., Bangladesh); and (iii) physically vulnerable but economically "rich" coastal communities (e.g., Sydney, New York). Table 1 outlines the main effects of relative sea-level rise on the natural system and provides examples of socio-economic system adaptations.

It is widely accepted that relative trends in sea-level rise pose a significant th of the economy of many island nations is based on tourism; this too will be affected by sea-level rise through its direct effects on infrastructure and possibly also indirectly by the reduced availability of financial resources in the market (Scott et al., 2012).

Coastal regions, particularly some low-lying river deltas, have very high population densities. It is estimated that over 150 million people live within 1 metre of the high-tide level, and 250 million within 5 metres of high tide. Because of these high population densities (often combined with a lack of long-range urban planning), coastal cities in developing regions are particularly vulnerable to sea-major cities, wetlands, and local economies. They based their work on a 10 per cent future intensification of storm surges with respect to current 1-in-100-year storm-surge predictions. They found that Sub-Saharan African countries will suffer considerably from the impacts. The study estimated that Mozambique, along with Madagascar, Mauritania and Nigeria account for more than half (9,600 km^2) of the total increase in the region's storm-surge zones.

Of the impacts projected for 31 developing countries, just ten cities account for two-thirds of the total exposure to extreme floods. Highly vulnerable cities are found in Bangladesh, India, Indonesia, Madagascar, Mexico, Mozambique, the Philippines, Venezuela and Viet Nam (Brecht et al., 2012). Because of the small population of small islands and potential problems with implementing adaptations, Nicholls et al. (2011) conclude that forced abandonment of these islands seems to be a possible outcome even for small changes in sea level. Similarly, Barnett and Adger (2003) point out that physical impact might breach a threshold that pushes social systems into complete abandonment, as institutions that could facilitate adaptation collapse.

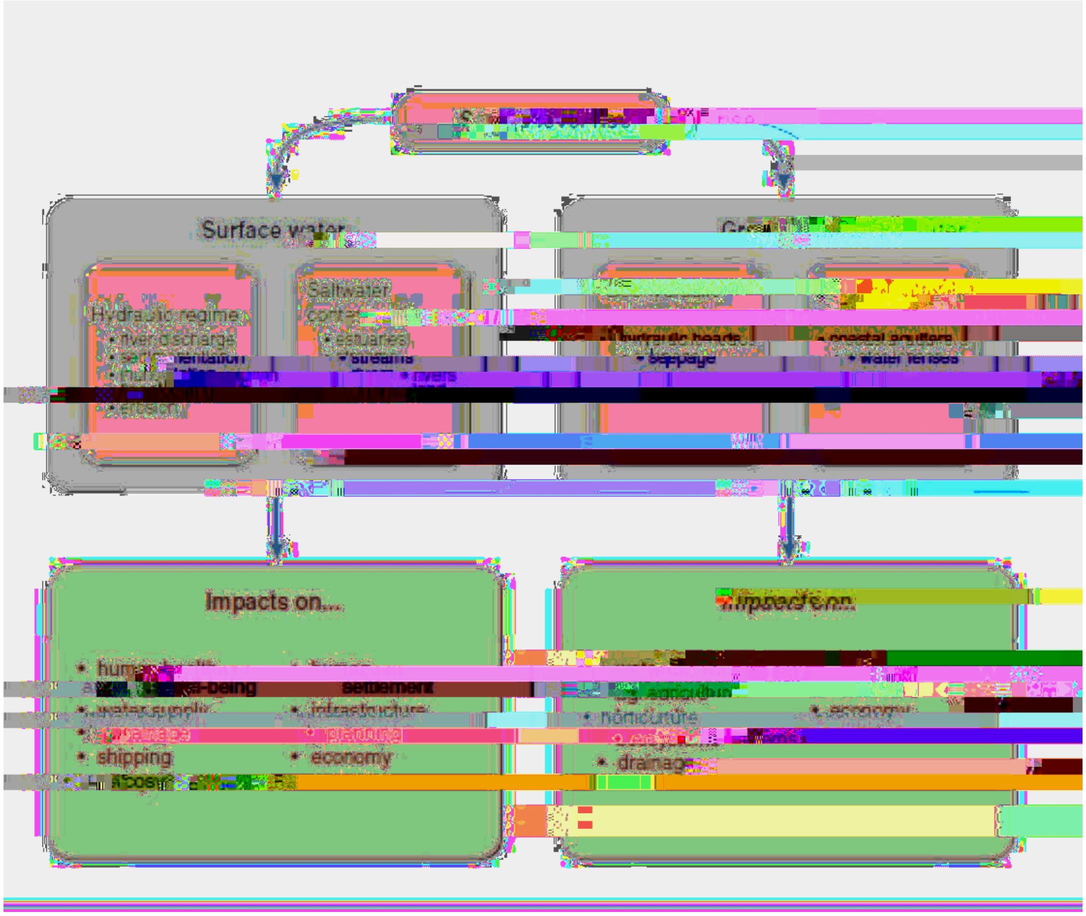

Figure 1. Effects of sea-level rise on water resources of small islands and low-lying coastal areas. Source: Based on Oude Essink et al. (1993); Hay and Mimura (2006).

Impacts of climate change on the hydrological cycle, and notably on the availability of freshwater resources, have been observed on all continents and many islands. Glaciers continue to shrink worldwide, affecting runoff and water resources downstream. Figure 2 shows the changes anticipated by the late 21st century in water runoff into rivers and streams. Climate change is the main driver of permafrost warming and thawing in both high-latitude and high-elevation mountain regions (IPCC WGII AR518.3.1, 18.5). This thawing has negative implications for the stability of infrastructure in areas now covered with permafrost.

Projected heat extremes and changes in the hydrological cycle will in turn affect ecosystems and agriculture (World Bank, 2012). Tropical and subtropical ecoregions in Sub-Saharan Africa are particularly vulnerable to ecosystem damage (Beaumont et al., 2011). For example, with global warming of 4°C (predicted by the high-end emissions scenario RPC8.5 in WGI AR5 FAQ 12.1), between 25 per cent and 42 per cent of 5,197 African plant species studied are projected to lose all their suitable range by 2085 (Midgley and Thuiller, 2011). Ecosystem damage would have the follow-on effect of reducing the ecosystem services available to human populations.

The Mediterranean basin is another area that has received a lot of attention in regard to the potential impacts of climate change on it. Several modelling groups are taking part in the MedCORDEX (www.medcordex.eu) international effort, in order to better simulate the Mediterranean hydrological cycle, to improve the modelling tools available, and to produce new climate impact scenarios. Hydrological model schemes must be improved to meet the specific requirements of semi-arid climates, accounting in particular for the related seasonal soil water dynamics and the complex surface-subsurface interactions in such regions (European Climate Research Alliance, 2011).

Even the most economically resilient of States will be affected by sea-level rise, as adaptation measures will need to keep pace with ongoing sea-level rise (Kates et al., 2012). As a consequence, the impacts of sea-level rise will also be redistributed through

Figure 4. Three long-term estimates of global zonal mean subsurface salinity changes according to (A) Durack and Wijffels (2010; ©American Meteorological Society. Used with permission.), analysis period 1950-2008; (B) Boyer et al. (2005), analysis period 1955-1998; and (C) Good et al. (2013),analysis period 1950-2012; all scaled to represent equivalent magnitude changes over a 50-year period (PSS-78 50-year^{-1}). Black contours show the associated climatological mean subsurface salinity for the analysis period. Broad-scale similarities also exist in the subsurface salinity changes, which suggest a decreasing salinity in ocean waters fresher than the global average, and an increasing salinity in waters saltier than the global average. However, regional differences, particularly in the high-latitude regions, are due to limited data sources, different temporal periods of analysis and different analytical methodologies.

3.2 Nutrients

Many different nutrients are required as essential chemical elements that organisms need to survive and reproduce in the ocean. Macronutrients, needed in large quantities, include calcium, carbon, nitrogen, magnesium, phosphorus, potassium, silicon and sulphur; micronutrients like iron, copper and zinc are needed in lesser quantities (Smith and Smith, 1998). Macronutrients provide the bulk energy for an organism's metabolic system to function, and micronutrients provide the necessary co-factors for metabolism to be carried out. In aquatic systems, nitrogen and phosphorus are the two nutrients that most commonly limit the maximum biomass, or growth, of algae and aquatic plants (United Nations Environment Programme (UNEP) Global Environment Monitoring System (GEMS) Water Programme, 2008). Nitrate is the most common form of nitrogen and phosphate is the most common form of phosphorus found in natural waters. On the other hand, one of arguably the most important groups of marine phytoplankton is the diatom. Recent studies, for example, Brzezinski et al., (2011), show that marine diatoms are significantly limited by iron and silicic acid.

About 40 per cent of the world's population lives within a narrow fringe of coastal land (about 7.6 per cent of the Earth's total land area; United Nations Environment Programme, 2006). Land-based activities are the dominant source of marine nutrients, especially for fixed nitrogen, and include: agricultural runoff (fertilizer), atmospheric releases from fossil-fuel combustion, and, to a lesser extent, from agricultural fertilizers, manure, sewage and industrial discharges (Group of Experts on the Scientific Aspects of Marine Environmental Protection, 2001; Figure 5).

An imbalance in the nutrient input and uptake of an aquatic ecosystem changes its structure and functions (e.g., Arrigo, 2005). Excessive nutrient input can seriously impact the productivity and biodiversity of a marine area (e.g., Tilman et al., 2001); conversely, a large reduction in natural inputs of nutrients (caused by, e.g., damming rivers) can also adversely affect the productivity of coastal waters. Nutrient enrichment between 1960-1980 in the developed regions of Europe, North America, Asia and Oceania has resulted in major changes in adjacent coastal ecosv4(d)2(al)10.d5v2darb11</MCID 1 >>Bst

4.2 Nutrients

Marine environments are unsteady systems, whose response to climate-induced or anthropogenic changes is difficult to predict. As a result, no published studies quantify long-term trends in ocean nutrient concentrations. However, it is well understood that imbalances in nutrient concentration cause widespread changes in the structure and functioning of ecosystems, which, in turn, have generally negative impacts on habitats, food webs and species diversity, including economically important ones; such adverse

Figure 5 (a) Trends in annual rates of applicati

Figure 6. Synthesis of the decadal-scale change in nutrient concentrations in the North Pacific Ocean in the last fifty years. (a) The blue area shows the waters for which a decreasing trend in nutrient concentrations was reported in the surface layer. (b) The pink area shows the waters for which an increasing trend in nutrient concentrations was reported in the subsurface. (c) Example of the nutrient change in the North Pacific Ocean. Five-year running mean of the annual mean concentration (mmol m^{-3}) of Phosphate concentration in the surface and North Pacific Intermediate Water (NPIW) of the Oyashio and Kuroshio-Oyashio transition waters from the mid-1950s to early 2010. (Tim7(he)9j0.eh (OT.313 0 Td[(1)-12.1(950s)91.96il7.1(mt)2.6(he4m)-6.4o(he)-362.8(7(he)9117(he)9117(he)9117(he)

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