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Early concepts and charts of ocean circulation

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Abstract – Charts of ocean currents from the late nineteenth century show that already by then the patterns of surface circulation in regions away from polar latitudes were well understood. This fundamental knowledge accumulated gradually through centuries of sea travel and had reached a state of near correctness by the time dedicated research cruises, full-depth measurements and the practical application of the dynamical method were being instituted. Perhaps because of the foregoing, many of the pioneering works, critical to establishing what the upper-level circulation is like, the majority of the charts accompanying them, and several of the groundbreaking theoretical treatments on the physics of currents, are only poorly known to present-day oceanographers.

In this paper we trace Western developments in knowledge and understanding of ocean circulation from the earliest times to the late-1800s transition into the modern era. We also discuss certain peripheral advances that proved critical to the subject. The earliest known ideas, dating from the Bronze Age and described by Homer, necessarily reflect severe limitations to geographical knowledge, as well as basic human predilections toward conjecture and exaggeration in the face of inadequate information. People considered the earth to be flat and circular, with the ocean flowing like a river around it. They also believed in horrific whirlpools, a concept that persisted into the Renaissance and which would later provide subject material for modern literature. From the Greek Classical Age, we find hydrologic theories of Earth's interior being laced with subterranean channels (Socrates) and all motion deriving from a divine force forever propelling the heavens toward the west, the *primum mobile* (Aristotle). These ideas, particularly the latter, dominated opinions about ocean circulation into the late Renaissance. By late Antiquity mariners had very likely acquired intimate knowledge of coastal currents in the Mediterranean, but little about them was reported in the Classical works. Following the dark and Middle Ages, when little progress was made, the voyages of discovery brought startling observations of many of Earth's most important ocean currents, such as the North and South Equatorial currents, the Gulf Stream, the Agulhas, Kuroshio, Peru, and Guinea currents, and others. The Gulf Stream appears to have been mapped as early as 1525 (Ribeiro) on the basis of Spanish pilot charts. Some currents were found to be westward, in the direction of the *primum mobile* as expected by theologians and philosophers, while others were not. The fifteenth through seventeenth centuries were marked by attainments of knowledge that increasingly taxed the abilities of science writers to reconcile new information with accepted doctrine. Consequences of this were descriptions of ocean circulation that questioned doctrine, yet were limited by it (Martyr; Gilbert; Bourne; Varen), while other descriptions disdainfully violated observation (Kircher; Happel). The expectation of a continuous westward oceanic flow around Earth in the direction of the *primum mobile* was so pervasive that it became central to arguments about a need for a passage through or around the Canadian north, and thus weighed significantly on the exploration and mapping of North America. Religious influences and the conceptual importance of the *primum mobile* waned by the close of the Renaissance and wind came to be seen as the primary cause of ocean currents (Dampier). The Gulf Stream (Franklin) and other North Atlantic flow patterns (de Brahm), as well as the southern Agulhas Current (Rennell), were mapped in the mid-to-late eighteenth century. Significant advances beyond these in determining the global ocean circulation came only after the routine determination of longitude at sea was instituted. The introduction of the marine chronometer in the late eighteenth century (Harrison) made this possible. By the end of the eighteenth century it was realized that water is a poor conductor of heat and, unlike that of freshwater, the density of seawater continues to increase as it is cooled to its freezing point; the far-reaching significance of the implied vertical convection and deep circulation of the ocean on the moderation of climate was immediately clear (Rumford), though observations were available almost exclusively from the ocean's surface. Largely because of the marine chronometer, a wealth of unprecedentedly-accurate information about zonal, as well as meridional, surface currents began to accumulate in various hydrographic offices. In the early nineteenth century data from the Atlantic were collected and reduced in a systematic fashion (Rennell), to produce the first detailed description of the major circulation patterns at the surface for the entire mid- and low-latitude Atlantic, along with evidence for cross-equatorial flow. This work provided a foundation for the assemblage of a global data set (Humboldt; Berghaus) that yielded a worldwide charting of the non-polar currents by the late 1830s. Subtleties such as the North Equatorial Countercurrent in the Pacific were revealed for the first time. During the next two decades, the western intensification of subtropical gyres was recognized (Wilkes) while numerous refinements were made to other global descriptions (Wilkes; Kerhallet; Findlay). Heuristic and often incorrect theories of what causes the circulations in the atmosphere and oceans were popularized in the 1850s and 1860s which led to a precipitous decline in the quality of charts intended for the public (Maury; Gareis and Becker). Such errors in popular theories provided motivation for the adoption of analytical methods, which in turn led directly to the discovery of the full effect of Earth's rotation on relatively large-scale motion and the realization of how that effect produces flow perpendicular to horizontal pressure gradients (Ferrel). The precedents for modern dedicated research cruises came in the 1860s and 1870s (i.e. *Lightning; Porcupine; Challenger; Gazelle; Vøringen*), as well as mounting evidence for the existence of a deep and global thermohaline circulation (Carpenter; Prestwich). The dynamical method for calculating geostrophic flow in the atmosphere (Guldberg and Mohn) and a precursor to our present formulation for quantizing surface wind stress (Zöppritz) were introduced in the 1870s. On a regional scale for the Norwegian Sea, the dynamical method was applied to marine measurements made at depth to yield a three-dimensional view of flow patterns (Mohn). Further insight into the deep circulation came slowly, but with ever increasing numbers of observations being made at and near the surface, the upper-layer circulation in non-polar latitudes was approximately described by the late 1880s (Krümmel).

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1. INTRODUCTION

Already by the late nineteenth century our present view of the oceanic surface circulation had been largely worked out and the transition had been made into the modern era of physical oceanography. Reversing thermometers and tightly-sealing water bottles had been developed, methods were in use for determining levels of dissolved substances in sea-water, field work was being conducted on dedicated research cruises, and theoreticians were advancing mathematical methods for evaluating dynamical balances. Serious study of the full-depth three-dimensional circulation was underway, thus establishing physical oceanography as a distinct science. Great amounts of effort by many individuals were required for this, yet much of the prerequisite work has been forgotten in the wake of all that has transpired since the opening of the modern era.

In this paper we examine the pre-twentieth-century development of Western concepts and charts of ocean circulation. We begin with the earliest thoughts about oceanic motion and proceed to show how through the ages these ideas evolved to reach the state at which they stood a little more than a century ago. A comprehensive treatment of all that has been written is well beyond present bounds, though we do wish to present a coherent account that considers in some detail the more important works. Most of our information comes from source materials dealing directly with ocean circulation, but we also touch upon societal factors and discuss certain advancements in other areas that proved critical and which are essential for context. The history leading up to the object study of the total circulation is long and complex. We hope this paper provides a meaningful perspective on its development.

2. THE ERA PRIOR TO SEA-GOING CHRONOMETRY

2.1. *Antiquity – broad generalities*

2.1.1. The earliest times and Homer. Seafaring is one of humanity's oldest organized activities. It began a hundred thousand years ago or more (LANDSTRÖM, 1961), though firm evidence for it dates back little more than nine thousand years (BASS, 1972), to the Neolithic Age when plants and animals were first domesticated. Many millenia before humans learnt to work with metals and adopted pictographic writing, littoral peoples had encountered coastal currents and doubtless had acquired a keen awareness of them. By the early Bronze Age, about 3500-3000 BC, active sea trading was well established throughout the eastern Mediterranean and along the Persian Gulf and Arabian Sea, so by then the early mariners must have had extensive experience with coastal currents. Further recognition surely came with the maritime supremacy acquired by the Minoans throughout the Mediterranean by 1500 BC, as well as with the westward expansion of Greek maritime colonialism that reached Italy prior to the Trojan War (~1200 BC). All this predated alphabetic writing, so what those people knew about currents is probably lost. By 800 BC the Phoenicians had established outposts beyond Gibraltar and sent expeditions north to Britain and south along the west coast of Africa, thereby navigating through the eastern portions of the Canary Current. They also made open-ocean voyages while navigating by the pole star; passages in the History of Herodotus led Alexander von Humboldt to think that they sailed as far west as the Sargasso Sea (MURRAY, 1895).

The Mediterranean seafaring tradition had been developing for thousands of years before information about the sea could be recorded in writing. The Greeks were the first to use alphabetic writing, in the 9th or early 8th centuries BC, prior to which was a gap of some 200-300 years following the collapse of Mycenaean culture and the disappearance of pictographic writing when the Greeks were probably illiterate (HOLLISTER, 1982). Typical of pre-literate societies, the primary method for preserving and passing-on information through the generations was the recital of poems, sung in meter so they could be easily remembered and passed on with a minimum of change. The greatest singer of poetry was Homer (~850 BC). Little is known about him, but he is credited with having brought together the large series of short poems which comprise the epics of the *Iliad* and the *Odyssey*. With the emergence of alphabetic writing, Homer's epics were transcribed and immediately assumed a singular importance in geography and history, much of which they retained down through the time of the Roman Empire and the rise of Christianity. But this importance was not uncontested. In a harsh critique, Eratosthenes (276-194 BC) categorized Homer's poems as being nothing more than pure fiction and he reproved those who attempted to infer facts from them. Hipparchus (146-127 BC), on the other hand, defended them by pointing out that the task of the old poets was to preserve information and that to be both interesting and entertaining they had to embroider on layers of fiction (DICKS, 1960). Further support came from the geographer Strabo (63 BC - 23 AD), who found Homer to be correct in many details (JONES, 1917). This has continued to be the prevailing, though not universal, opinion. CERVENY (1993) has used Homer's *Odyssey* to reconstruct a chronology of meteorological conditions in the eastern Mediterranean.

The accepted configuration of land and ocean may be seen in the *Iliad*'s description of Hephaistos creating an immortal shield for the protection of Achilles in the Trojan War. Several concentric annuli of scenes depicting paradigms of human life were engraved out from the center of the shield. Near the end of Book XVIII, Homer says Hephaistos "put the mighty power of Ocean's river upon the solid shield's far outer rim" (HULL, 1982). Earth was envisaged as a disk encircled by a moving stream of ocean, and this concept was repeatedly taken up in the *Odyssey*; for example, when near the beginning of Book XI it is recounted that after a day's sail from the island of Æaea Odysseus and his men "attained Earth's verge and its girdling river of Ocean..." (SHAW, 1932).

The theory of Earth being a disk surrounded by an immense river long predated Homer. Pictorial evidence links the idea with the Minoans of the third millenium BC (DICKS, 1960), and more clearly with the ancient Babylonians and Egyptians (DAMPIER, 1971). By Homer's time no inhabitant of Greece had ever seen the Atlantic or Indian oceans, but because trade routes had existed between Greece and western Europe and Arabia since Neolithic times (e.g., ROBINSON, 1967), the Greeks would have long been aware about distant seas through legend. It would have been natural for them to extrapolate and to assume that land was bounded on all sides by water - an argument advanced in the first book of *The Geography of Strabo* (ca. 64 BC - 23 AD) (JONES, 1917). As to why the ocean should move as a river, Strabo summarized several possible explanations. These included the idea that the motion was connected with tides, and while Strabo considered all of them to be ill-founded, he offered no plausible explanation himself. It seems likely that the notion derived from the millennia-old knowledge of coastal currents in the eastern Mediterranean, which may have been augmented by stories of currents from the coasts of western Europe and the Indian Ocean. Where there is ocean there are currents, and if the ocean were continuous around Earth then one might expect a general, stream-like flow. When he chronicled the events of the Trojan War and the travels of Odysseus, Homer expressed the Earth-disk, ocean-river concept as though it was an accepted fact, which ostensibly was concurred upon by Mediterranean people well before 1200 BC. As a concept it may have evolved over a longer period of time than Homer's works have subsequently been preserved.

During Homer's time, Phoenicia was the controlling maritime power in the Mediterranean. Part of the Phoenician success stemmed from a policy not only of suppressing geographical knowledge for purposes of military security and trade advantage, but apparently also of spreading fantastic and misleading information (e.g., STEFANSSON, 1947). The Phoenicians were certainly not the only inventors of myths and stories, many of which derived from rare and poorly observed oceanic events that were easily misinterpreted, such as localized vortical motions. It is likely that fantastical tales of whirlpools had been told and retold over many centuries by superstitious and imaginative sailors who had encountered short-lived turbulent vortices within channels. At the limits of Homer's geographical knowledge, where conditions favor such vortical motion, is the Strait of Messina. In Book XII of *Odyssey*, after Odysseus and his men had returned to Æaea, the goddess Circe explained to them that on their route home to Ithaca lay the enormous Charybdis that thrice-daily sucked down the sea and spewed it out again in an awful sight. Later in the chapter, during their voyage to Ithaca, Odysseus and his men saw that "Charybdis in her terrible whirlpool was sucking down the sea; and vomiting it out again like a vat on a hot fire. The briny water did gush from her abyss in such a seethe that the froth of it bespattered the tops of both rocky walls. Whenever she swallowed-in the yeasty ocean one could see right down the whorl of her maw. At its very bottom the sea's floor showed muddy and dark with sand. The cliffs about thundered appallingly". It is widely accepted that Homer's Charybdis was set in the Strait of Messina, separating Sicily from the Italian peninsula. Homer's account of Charybdis, likely fuelled by Phoenician tales, survived remarkably well intact as a factual model for reports of other whirlpools. such as the Maelström, for more than two millennia down to the late Renaissance, and fictionally into the nineteenth century in Edgar Allen Poe's *A Descent into the Maelström*.

The factual basis for the story of Charybdis lies with the geomorphology of the Mediterranean and with its semi-diurnal tides (DEFANT, 1961; BIGNAMI and SALUSTI, 1990). This may seem unexpected at first because tides in the Mediterranean are very weak with amplitudes of less than 20cm and are seldom noticeable. However, the Strait of Messina is narrow, constricting down to ~3km in width, and its sill depth is just 80m. To the north of the sill the bottom slopes more steeply into the Tyrrhenian Sea than to the south into the Ionian Sea. The tides north of the strait (~16 cm) are nearly 5 hours out of phase with those to the south (~10 cm). As a result of these tides the difference in sea level can exceed 5cm over a distance as little as 3km, enough to generate currents of 200cm.s^{-1} (4-5 knots). When the currents change direction, stream convergences occur at places within the strait that lead to turbulent disturbances which are amplified by differences in water properties of the convergent streams, and occasionally by winds. Furthermore, the overall configuration of the Mediterranean permits a standing wave in both the eastern and western basins, and as a result of the effects of Earth's rotation an amphidromic transform oscillation can be produced within the strait. All these factors together can produce eddies having both vertical and horizontal axes, sometimes acquiring large dimensions. The most important eddies develop off Cape Peloro (Charybdis) and in front of the harbor entrance to Messina. The strong tidal currents and the eddies they generate must have been very impressive, if not horrifying, to the ancient mariners.

Homer's Charybdis had a thrice-daily frequency, one less than the combined two northward and two southward flows per day resulting from the semi-diurnal tides. As the tides through most of the Mediterranean are too small to be noticed without making precise measurements, and since at the time the connection between the Moon and tides was yet to be made, Homer could have had no idea that this phenomenon was tide-related (if indeed he even knew of tides at all). Thucydides (~401 BC) in his history was also unable to make the connection when he described the Strait of Messina as being "naturally considered dangerous; for the strait is narrow, and the sea flowing into it from two great oceans, the Tyrrhenian and Sicilian, is full of currents" (IV.24 in GODOLPHIN, 1942). But later in the Classical Age, after the tides were ascribed to the Moon (Section 2.1.2), Eratosthenes recognized the turbulence as being tide-induced (he even attempted to measure the currents in relation to the phase of the Moon). Commenting on Homer's inaccuracy about the frequency, Strabo suggested: "it may be that Homer really strayed from the fact on this point, or else that there is a corruption in the text" (JONES, 1917). It is also possible that current reversals taking place during the dark of night went unrecognized by the early sailors who ventured into the region.

2.1.2. The Classical Age. The idea of Earth being a disk surrounded by an ocean-river was repeated by Hesiod (~800 BC) and Hecataeus (~500 BC), but from a philosophical perspective regarding the perfectness of shapes, Pythagoras (~580-500 BC) put forth the theory of Earth being a sphere, though the ocean could still flow around the dry part. This concept gained wide consensus as more and more geographical knowledge was accumulated. In a compilation of all known geographical information, Herodotus (484-425 BC) agreed with the global extent of the outer ocean, saying (I.203 in GODOLPHIN, 1942): "The sea frequented by the Greeks, that beyond the Pillars of Heracles, which is called the Atlantic (named after the god Atlas according to Plato), and also the Red Sea, are all one in the same sea". But he went on flatly to reject the speculation of the ocean being a river. While discussing theories about the source of the Nile River, one having the Nile start as a landward flow from the Earth-encircling river of ocean, Herodotus wrote (II.23): "As for the writer who attributes the phenomenon to the ocean, his account is involved in such obscurity, that it is impossible to disprove it by argument. For my part I know of no river called Ocean, and I think that Homer, or one of the earlier poets, invented the name, and introduced it into his poetry". He reiterated his skepticism in other passages, as for example in IV.8: "Now some say that the Ocean begins in the east, and runs the whole way round the world; but they give no proof that this is really so".

Herodotus made an interesting comment when he casually mentioned the tides in the Red Sea (II.11): "In this sea there is an ebb and flow of the tide every day". Homer made no direct mention of tides, so it is unknown whether he, and other writers who preceded Herodotus, were aware of their existence. Heredotus's statement about tides is the earliest we have seen, but the perfunctory manner in which it was said indicates that the Greeks had acquired a basic knowledge of tides sometime before, likely as a result of expansions in trade.

In contrast to some geographers and historians who felt that questions unanswerable by evidence need not be answered, philosophers strove to provide explanations of all phenomena. Often the only way open to them to accomplish this was through the use of logic and first principles, which was deemed sufficient if done carefully enough. One issue that was beyond the realm of observation, but highly perplexing and ripe for a theory, was the hydrologic cycle. The vast amounts of water carried by rivers, such as the Nile, were easy to observe but difficult to account for in terms of sources and sinks. Various theories were offered, some touching on the effects of precipitation and evaporation, but these processes were very poorly understood and their true importance could not have been appreciated. So other mechanisms were invoked.

Socrates (470-399 BC), the first of the trio of ancient Greeks who laid the foundations of Western philosophy (followed by Plato and Aristotle), wrote nothing himself, but his pupils set down his beliefs, for which he was condemned by the court in Athens to death by poison. Sometime after Socrates's death his devoted student Phaedo, who was with him to the end, gave an account of his last hours to a number of friends. In *Phaedo*, one of Plato's (428-348/7 BC) dialogues, Socrates is quoted as having put forth a theory that would re-emerge at intervals over the next two millennia, and at times enjoyed considerable popularity. This was the idea of subterranean channels: "In the earth itself, all over its surface, there are many hollow regions, some deeper and more widely spread than that in which we live (he had previously described humans as living in depressions on a spherical Earth where water and air had collected), others deeper than our region but with smaller expanse, some both shallower than ours and broader. All these are joined together underground by many connecting channels, some narrower, some wider, through which, from one basin to another, there flows a great volume of water – monstrous unceasing subterranean rivers of waters both hot and cold – and of fire too, ... One of the cavities in the earth is not only larger than the rest, but pierces right through from one side to the other." It is of this that Homer speaks when he says, "Far, far away, where lies earth's deepest chasm" (*Iliad* 8.14), while elsewhere both he and many other poets refer to it as Tartarus (also thought to be the dire destiny to which immoral persons were condemned). Into this gulf all the rivers flow together, and from it they flow forth again, and each acquires the nature of that part of the earth through which it flows. The cause of the flowing in and out of all these streams is that the mass of liquid .... oscillates and surges to and fro, ... Among these many various mighty streams there are four in particular. The greatest of these, and the one which describes the outermost circle, is that which is called Oceanus" (HAMILTON and CAIRNS, 1961). Aside from preserving the thoughts of Socrates, Plato seems to have added little himself to ideas concerning the ocean.

Aristotle (384-322 BC) was much more influential, though largely indirectly. In his surveys of all human knowledge and his theories about the universe, Aristotle concerned himself more with generalities rather than specifics. Unfortunately, all the works which Aristotle personally published were lost during the first centuries of the Christian era, so all that survives are his writings that were not intended for dissemination, but which were gathered together and published by his followers. There are 47 such works that have been attributed to Aristotle, and these dominated Western and Muslim thought on many subjects for nearly 2,000 years.

Aristotle discussed motion at great length, which he considered to be relative to a stationary and spherical Earth located at the center of the universe. In Book VII of *Physics*, Aristotle wrote: "Everything that is in motion must be moved by something. For if it has not the source of its motion in itself it is evident that it is moved by something other than itself, for there must be something else that moves it. .... Since everything that is in motion must be moved by something, let us take the case in which a thing is in locomotion and is moved by something that is itself in motion, and that again is moved by something else, and so on continually: then the series can not go on to infinity, but there must be some first mover" (the *primum mobile*) (Barnes, 1984). In the final book of *Physics*, Aristotle set down a series of arguments to conclude that the first mover must itself be unmoved, that it acts on the circumference of the universe, and "that it is indivisible and is without parts and without magnitude." In Book II, *On the Heavens*, he expounded on the subject, asserting that the shape of heaven is spherical and that it encloses successively smaller spheres down to the center (Earth). The movement of the outermost sphere was held to be uniform, with increasingly irregular motions appearing in the lower spheres. Through these discussions Aristotle implied the first mover to be divine, and later in *Metaphysics* he stated it explicitly. It was this premise, that the first mover should be divine, that gained unanimous theological endorsement during the rise of Christianity and was to prove so important in shaping the Renaissance view of ocean circulation and in the exploration and mapping of the New World (Section 2.3.3).

It is evident that Aristotle disagreed with the theory of an Earth-encircling river of ocean. In Book I of *Meteorology*, he described "a circular process that follows the course of the sun (the vertical motion of air and moisture in response to solar heating).... When the sun is near, the stream of vapour flows upwards; when it recedes, the stream of water flows down; and the order of sequence, at all events, in this process always remains the same. So if 'Oceanus' had some secret meaning in early writers, perhaps they may have meant this river that flows in a circle about the earth". He also dismissed the idea of a huge subterranean cavern from which all rivers flow. In Book I of *Meteorology*, Aristotle conceded the existence of smaller chasms and cavities within Earth that receive water, citing as evidence the occurrence of rivers flowing into valleys without surface outlets to the sea. In Book II, however, he categorically stated that "the theory of the *Phaedo* about rivers and the sea is impossible" (because it required water to flow upward).

Aristotle offered little direct information regarding the sea's motions, except for what we find in Book II of *Meteorology*: "The whole of the Mediterranean does actually flow, according to the depths of the basins and the number of rivers. Maeotis (Sea of Azov) flows into Pontus (Black Sea) and Pontus into the Aegean. After that the flow of the remaining seas is not so easy to observe. The current of Maeotis and Pontus is because of the number of rivers (more rivers flow into the Euxine (also Black Sea) and Maeotis than into areas many times their size), and to their own shallowness. For we find the sea getting deeper and deeper. Pontus is deeper than Maeotis, the Aegean than Pontus, the Sicilian Sea than the Aegean; the Sardinian and Tyrrhenic being the deepest of all. (Outside the pillars of Herakles the sea is shallow owing to the mud, but calm for it lies in a hollow.)" Although he did not state it directly, the motion he described is generally towards the west, in conformity with the motion of his celestial spheres.

Of the 47 works attributed to Aristotle, the authenticity of 16 has either been seriously questioned or altogether dismissed. Their true authors are unknown, though they do reflect other thinking of the period and perhaps allowed scholars in later centuries some discretion in selecting materials supportive of particular points of view. Among the suspect works is *Problems*, where in Book XXIII the question was posed: "Why is it that sometimes vessels journeying over the sea in fine weather are swallowed up and disappear so completely that no wreckage ever is washed up?" Such events were attributed to whirlpools, a specific example being that in the Strait of Messina.

The reporting of this phenomenon was not in Aristotle's usual style. Even more at odds with his usual style are passages from *On the Universe*, whose authenticity is now dismissed. In this, there appears a mixture of Aristotelian and older theories presented with greater piety than in Aristotle's actual works. It begins with a short description of the spheres of the universe, and goes on to make approving reference to a river-like ocean, which was contested by Aristotle in *Meteorology*. It contains factual information, probably unavailable to Aristotle, about the surface flow from the Atlantic into the Mediterranean: "Again, the sea which lies outside the inhabited world is called the Atlantic or Ocean, flowing round us. Opening in a narrow passage towards the West, at the so-called Pillars of Heracles, the Ocean forms a current into the inner sea, as into a harbour; then gradually expanding it spreads out". The unknown author also talked of subterranean channels, and while not referring to any particular sea, wrote: "Many tides and tidal waves are said always to accompany the periods of the moon at fixed intervals".

It is unlikely that Aristotle could have made such a statement about the tides, considering that the connection between the relative motion of the Moon and tides was made only around the end of his life. This was done by Pytheas (~330 BC), information about whom is fragmentary, though it is known he was able to elude Phoenician guardians of the Strait of Gibraltar to sail a small craft (larger than that used by Columbus to cross the Atlantic) from Marseilles into the Atlantic and turn north toward Britain. He sailed in midsummer to the northern tip of Scotland, followed Scottish instructions on to Iceland, and then sailed beyond Iceland for another 150 km or so before being stopped by ice and fog in the East Greenland Current. Pytheas also landed in Ireland and explored eastwards to the Baltic. Following his return to Marseilles he wrote a book, *The Ocean*, which is now lost, moreover there are no surviving works written by authors who themselves had read it. But there are many second-hand references to *The Ocean*, made by Strabo, Pliny, Solinus, and others, and these recall several consistent details. *The Ocean* was probably the earliest book written about marine science. Another lost book that dealt with the subject of sailing directions, *The Periplus*, may have also been written by Pytheas. The second-hand information about Pytheas shows that he knew how to determine latitude, used astronomical navigation, and, remarkably, deduced the connection between the relative motion of the Moon and the semi-diurnal tides. His story, along with commentary by Fridtjof Nansen, has been retold by STEPHANSSON (1947).

With the conquests of Alexander the Great (356-323 BC) and the physical observations made by his legions, Greek philosophers were confronted with the difficult challenge of explaining the tides. A host of opinions were formed and debated, with many of the hypotheses subsequently passing on to medieval western Europeans (DEACON, 1971). But little of the factual information about coastal currents, which must have been familiar to mariners, made it into the literature. Eratosthenes (276-194 B.C.) was interested in the currents in the Strait of Messina, but all we have about his ideas and knowledge is what was written later by Strabo (I.3.11 in JONES, 1917). Eratosthenes is better known for calculating the size of Earth: realizing that at noon the Sun is directly overhead present-day Aswan at the time of the summer solstice, while at the same time being seven degrees from vertical at Alexandria, he deduced the circumference of the globe to within 0.5-17% of its actual value of ~40,000 km, depending on the exact length of unit he used (the stadium, ranging from 179 to 218m). He also proposed that the similarity of tides in the Atlantic and Indian oceans meant that the two seas must be connected and that the known world of Europe-Asia-Africa is an island, around the southern part of which one could sail from Spain to India. Poseidonius (135-51 BC) rejected the idea and provided another estimate for the size of Earth, saying that one could sail westwards from Europe for 70,000 stadia (~12,500-15,300 km) and reach India. Columbus later approved of this estimate and used it, along with others of similar size, to secure royal backing for his first westward voyage intended for the Indies (DAMPIER, 1971).

The rise of the Roman Empire and growth of Mediterranean enterprise in western Europe led to a steady accumulation of information about tides that went without equivalent gains in knowledge about ocean currents in general. The subject of currents was left entirely untouched by renowned geographers such as Pliny the Elder (23-79 AD) (RACKHAM, 1938) and Ptolemy (ca.90-168 AD) (STEVENSON, 1932), the latter providing a synthesis of what had been contributed by those preceding him–Hipparchus, Eratosthenes, and especially Marinus (ca. 70-130 AD). Though accounts of currents were most likely available to him, Ptolemy may have elected to pass them over because, "Carefully observed phenomena should be preferred to those derived from the accounts of travellers". He also took to task the pre-historic concept transmitted by Homer: "The known part of the earth is so situated that it is nowhere entirely walled around by the ocean, except only in the case of the land of Raptis, which belongs in part to Africa and in part to Europe, according to the testimony of the ancients".

In view of the foregoing, and except for the broad generalities outlined by Aristotle, it appears that Greek scholars attached little importance to currents, perhaps either because the available information was contradictory, or they could discern no pattern. What is certain, however, is that the concepts put forth during Antiquity, principally the Aristotelian concepts of motion, heavily influenced the way ocean circulation would be viewed far beyond the era.

2.2. *Middle Ages – Western stagnation, Arab progress*

Following the collapse of the Roman Empire (~395 AD) in western Europe and the resulting loss of centralized government, little progress was made by Europeans in the marine sciences for nearly a thousand years. Strongly contributing to this lack of progress was the patristic theology of early Christianity. Neo-Platonism, a rationalist philosophy holding that the ultimate reality of the universe is spirit, dominated Christian thought, as did the concepts of sin and judgement that further eroded interest in secular knowledge for its own sake. The influential Saint Ambrose (339-397), the bishop of Milan who endeavored to reconcile mystical Greek philosophy with church theology, contended that, "To discuss the nature and position of the earth does not help us in our hope of the life to come" (DAMPIER, 1971). Christian attitudes became antagonistic, even intolerant, to secular thought. A portion of the Library of Alexandria was destroyed in 390 by Bishop Theophilus, and the last mathematician of Alexandria was killed by a Christian mob in 415. Natural knowledge came to be valued only as a means of illustrating theological doctrine.

The few writers of science in this atmosphere of hostility toward observation and experiment were predominantly members of the clergy. They used literary methods in which past opinions of natural phenomena were thought to have greater importance than present realities. This made the study of previous concepts, cast in terms of scriptural interpretations, the accredited way to arrive at the truth. An example comes from the era's most prominent and representative work, *Etymologiae* (or *Origins*), a twenty-book composition by Bishop Isidore of Seville (?600-636). In the thirteenth book he described the world as a whole. Using a passage from the Bible as supporting evidence, he sided with Homer in describing the solid Earth as being circular like a wheel with the ocean flowing round it on all sides (KIMBLE, 1938).

Advances made during mediaeval times came mainly from the Arab world. Following the death of Muhammad in 632 and the rapid succession of military conquests and spread of Islam (during which the remainder of the Library of Alexandria was destroyed by Muslims in 640), many of the more important Greek philosophical and scientific writings were acquired by the Arabs. Around the year 800, the powerful caliph Hārūn-al-Rashid pushed for the translation of the Greek writings, and thus helped to initiate the great period of Arab learning. Progress was slow at first, because new vernacular suitable for conveying the subject matter had to be worked into the Syriac and

Arabic languages (DAMPIER, 1971). Once accomplished, celestial navigation, as invented by the Greeks, was improved upon and used by Arab seamen in the 8th-12th centuries to ply trade routes across the Indian Ocean and into the western Pacific toward destinations as far off as China. Commodities from the Far East were thus brought to Arabia, as well as over land routes, and from there they were sold to Europeans in the eastern Mediterranean. European interest in the East was kindled, and without the Greek-Arab development of trigonometry and astronomical navigation the later European voyages of exploration would not have been possible (ALEEM, 1981).

The principal routes used by Arabs crossing the Indian Ocean were in its northern portions, where, even with the aid of crude navigation, the set caused by currents would be difficult to distinguish from set caused by wind, as they are in roughly the same direction during each monsoonal cycle; the seasonal reversals of currents might thus have passed unnoticed by navigators (WARREN, 1966). However, by as early as the year 846 these reversals had been described by the geographer Ibn Khordazbeh (ALEEM, 1967), and again in 947 by El-Mas'údí in the Arab encyclopedia *Meadows of Gold and Mines of Gems* (a deceptive title used to lure readers) (WARREN, 1966). Also in the work by El-Mas'údí, a westward current was described as flowing along the equator in the Indian Ocean, that was reported to run in the same direction as the motion of the heavens above (DEACON, 1971). This association clearly came from Aristotelian philosophy.

2.3. *Early Renaissance – the major currents discovered*

Far beyond the scope of the literary and artistic revival that began in Italy during the fourteenth century was a much larger and more complicated redirection of European capacity and vigor as a whole. Unlike the arts, humanities, and basic sciences, whose advancements were driven by intellectual forces, a better understanding of the ocean resulted chiefly from the economic and military expansions made possible by extended sea travel. These expansions were fuelled by desires for material wealth, which were greatly stimulated by the exotic accounts of riches and spices in the East given by Marco Polo (1254-1324) and Nicolo de' Conti (1395-1469). Without the prospects of material gain there would have been little interest on the parts of European royalty to finance any major sea-going expedition. Scandinavian accounts of land west of the Atlantic, first sighted in 985 or 986 by Bjarni Herjulfson when he was blown off course on a voyage from Iceland to Greenland, and later landed upon by Leif Ericsson in 1001 or 1002, were known to a certain extent within the learned society of Europe. Before its decline in the late fourteenth century, there existed along the southwestern coast of Greenland a Nordic society of more than three thousand. Roman Catholic bishops were assigned to the Greenland diocese (though they remained in Europe), and an account of Viking discoveries was given as early as the eleventh century by the Bishop Adam of Bremen in *Gesta Hammaburgensis ecclesiae pontificum* (KLEMP, 1976). Following the voyage of Lief Ericsson, the Scandinavian people of Greenland obtained wood from the northeast coast of America, and they tried without success to establish colonies there, while remaining in intermittent contact with Icelanders and Europeans. But Norse knowledge of forests and aboriginal inhabitants in the western lands did little to instil ambitions in others to explore the region. Their discoveries were ignored by the rest of Europe.

From the thirteenth century into the fifteenth, Christendom experienced a geographical recession, whereas the Islamic sphere of influence expanded. Commodities from the East could only reach Europe along trade routes passing through regions controlled by Hindus and Muslims, who at each juncture exacted higher prices in order to make profits. By the early fifteenth century the combination of high demand and exorbitant prices of Eastern goods had merchants and sailors throughout Europe speculating about new routes to the East. Celestial navigation had reached Europe, and in 1409 Ptolemy's *Geography* was translated into Latin. The prospect of a sea route to the East became more inviting, though it still was unknown whether the Atlantic and Indian oceans were continuous south of Africa. Even if it were known, such a route remained well beyond the limits of the era's ships. It was not until the fourteenth century that steering oars (the "starboard", always on the vessel's right side) were replaced by stern rudders (LANDSTRÖM, 1961). The use of multiple masts and variants of lateen rigging had appeared in the Mediterranean, but ships used in the stormy North Atlantic remained single-masted and square-rigged. These cogs could make little headway when working continuously against the wind, so even though such a vessel could have easily crossed the Atlantic to the Caribbean with the trade winds, it is highly unlikely it would have ever returned. New technologies in ship building, navigation and cartography had to be developed if Europeans were to acquire the basic essentials for sailing the open ocean and circumventing Arab monopolies in trade with the East.

2.3.1. Prince Henry; Christopher Columbus; Peter Martyr. In celebration of a friendship treaty signed in 1411 between Portugal and Castille, a crusade was sanctioned against the Muslim city of Ceuta, a commercial center on the Moroccan coast opposite Gibraltar. Portugal's King John I assigned the task of building the required fleet to his third surviving son, Prince Henry (1394-1460). In 1415, at just the age of twenty-one, Henry led the attack on Ceuta and easily defeated the unprepared defenders of the city. There the attackers found storehouses filled with prized goods from the Sahara and the East, thus whetting the Portuguese appetite for further conquest of Africa. Henry was immediately appointed governor of Ceuta, and hence learned the sources of the captured wealth. He organized an expedition to capture Gibraltar from the Muslims, but once the expedition got underway King John ordered its recall. This was a fortunate turn of events for the history of ocean exploration, for after returning to Portugal in 1418 and having been made a duke, the disappointed Henry retired from the court and took up residence near Cape Saint Vincent, the southwestern corner of Europe called the "Sacred Promontory" by Marinus and Ptolemy (BOORSTIN, 1985). The local village of Sagres acquired its name from it. At Sagres, Henry focused his ambitions on conquest and the conversion of pagans to Christianity, and as a symbol of his theocracy he had the sails of all his ships embellished with the large red cross that would become famous. In 1420 he was made grand master of the Court of Christ, a supreme order sponsored by the pope which became an important source of his funds.

Realizing that the available technology was inadequate for achieving his goals, Henry began to summon experts from all over Europe to Sagres. The resulting assembly of seamen, cartographers, astronomers, shipbuilders and instrument makers might well be called the first school of oceanography, and their activities set the stage for European exploration of the world. Henry's impact on history has been regarded by some as being without mortal parallel (GUILL, 1980). Although he personally never participated in any significant voyage of discovery, Henry was nonetheless surnamed the Navigator. The systematic keeping of logbooks and annotation of charts were initiated, the astrolabe was replaced by the quadrant, and the revolutionary Portuguese caravel was developed and built at the nearby port of Lagos. For the first time there was the need for a manoeuvrable ship capable of carrying stores and men on long journeys of exploration, and the caravel with its shallow draft, relatively large capacity and lateen sails proved to be an excellent design for meeting the challenge. It was a ship that could go virtually anywhere in the world, and still return home.

Even with these great advances, the human state of mind had to be overcome as well. According to Gomes Eanes de Zurara (1410-1473/4), the chronicler of Henry's work, "yet there was not one who dared to pass that Cape of Bojador (on the Western Sahara coast southeast of the Canary Islands) and learn about the land beyond it, as the Infant wished. And to say the truth this was not from cowardice or want of good will, but from the novelty of the thing and the wide-spread and ancient rumor about this Cape, that had been cherished by the Mariners of Spain from generation to generation. ... For, said the mariners ... the sea is so shallow that a whole league from land it is only a fathom deep, while the currents are so terrible that no ship having once passed the Cape, will ever be able to return" (BEAZLEY and PRESTAGE, 1896).

It took fifteen years of effort, from the time he started his work at Sagres, for Henry to succeed in getting anyone to sail beyond Cape Bojador; it was finally accomplished by Gil Eannes in 1433. In the years that followed Henry established a lucrative trade in slaves captured in the northern Gulf of Guinea, but he never saw his men cross the equator. He died in 1460, and the Portuguese continued to press farther south, gradually learning about the doldrums and associated changes in winds and currents (GUILL, 1980). Few records of the early voyages have survived, leaving little about what was learned of ocean currents during and shortly after Henry's time. This is partly because of a physical deterioration of the records, and to the records being withdrawn from archives for official use and never returned, but it is mainly a result of a policy of secrecy that existed from the first of Henry's voyages (GREENLEE, 1938). The history-shaping legacy is that the technological advances made by Henry's coterie were picked up by other Europeans, and these were essential to future acquisitions of knowledge about the circulation of the seas.

Portuguese advances southwards along the African coast were slow, and, because it was not known for certain if the Atlantic and Indian oceans were connected south of Africa, the Florentine cosmographer Paola Toscanelli (1397-1482) was consulted about a possible westward route to the Indies. In a letter to the King of Portugal in 1474, Toscanelli drew from Marco Polo's descriptions of Japan lying some fifteen hundred miles off the coast of a vast Asian continent to propose that no great amount of sea had to be sailed toward the west in order to reach the coveted lands of riches. Shortly afterward, in 1476, the young and still illiterate Christopher Columbus was marooned off the coast of Portugal, and instead of returning to his native Genoa he took up the trade of making mariner's charts in Lisbon with his brother. There Columbus learned to read and write, and he also learned of Toscanelli's letter, in 1481 or 1482. He solicited and received more information, including a chart, from Toscanelli himself. Evoking Biblical passages and accounts from Marco Polo, while also artificially reducing the distance of a degree by using the Italian mile, Columbus argued that the Indies were only 6200km west of the Canary Islands, a figure even less than that proposed by Poseidonius in the first century BC. In 1484 Columbus proposed his *Enterprise of the Indies* to the King of Portugal, but was turned down.

Serving further to dissuade the Portuguese from attempting a westward voyage was the long-awaited rounding of the southern terminus of Africa in 1486 by Bartolomeu Diaz, who, after having encountered several strong gales, named the southernmost promontory *Cabo da Boa Esperanga*, or Cape of Good Hope. There appear to be no surviving accounts of the Agulhas Current from that voyage. But on the second rounding, by Vasco da Gama in 1497, a southward current was met near Algoa Bay (Port Elizabeth) of such strength that the flotilla was set steadily back for three days (LEY, 1965). The scale of the current was not immediately obvious, which can be inferred from a memorandum issued prior to the start of the Cabral voyage in 1500. In this, da Gama gave instructions on how to round the Cape, but he spoke only of weather (GREENLEE, 1938). By the mid-1500s, however, the Portuguese knew enough about the Agulhas Current to stay well out to sea as they rounded southern Africa on the way out to India, but to stay near the coast on the homeward voyage. More details of the history of this current can be found in papers by PEARCE (1980) and LUTJEHARMS, DE RUIJTER and PETERSON (1992).

The existence of open-ocean currents in the Atlantic had been suspected for some time before this; strange drift articles were occasionally found at Porto Santo in the Madeira Islands, also a piece of an unknown type of wood had been recovered 450km west of the Cape Verde Islands. Such items could have come only from land on the far side of the Atlantic by way of currents, and

Columbus used this as another argument for sailing west (KOHL, 1868). But once southern Africa had been rounded, Portugal lost interest in a westward route. So Columbus was compelled to turn to Queen Isabella of Spain, whose support he succeeded in gaining after several attempts.

Using a sounding line and lead in September 1492, Columbus made the first observations of the (North) Equatorial Current, which he observed again during his second and third voyages (1494-98) (KOHL, 1868). The primary function of the sounding line was not for detecting currents, but was deployed out of fear of running aground. An influential historian of the early sixteenth century was Peter Martyr d'Anghiera (1457-1526), an Italian living in Spain who wrote a treatise in Latin, *De Orbe Novo Decades*. In the first decade of eight, Peter Martyr wrote that Columbus (from an English translation by EDEN (1555, page 32)), "euer sent one of the smaulest carauelles before, to try the way with soundinge: and the byggest shyppes folowed behynde". In August 1498 on his third voyage, Columbus made the first observation of the Guiana Current in the vicinity of Trinidad. Also according to Peter Martyr (EDEN, 1555, p. 30), "No greate space frome this Ilande, euer towarde the weste, the Admirall saith he fownde so owteragious a faule of water, runninge with such a violence from the Easte to the Weste, that it was nothynge inferioure to a myghty streame faulynge from hyghe mountaynes". He also confessed, that "since the fyrst daye that euer he knewe what the sea mente, he was neuer in suche feare". Columbus had sighted the South American continent, but thought it was only an island in the Indies, so he had no concept that he was sailing along a boundary current which was much more intense than any mid-basin flow (even at his death Columbus contended that the lands he discovered were in the Far East). Columbus had also discovered Spanish articles washed up on beaches in the Caribbean, findings which he attributed to the general westward currents he considered to move around the world with the sky (KOHL, 1868). His description was thus not unlike that of the Equatorial Current in the Indian Ocean given by El-Mas'údí four and a half centuries earlier, both having been derived from ancient Greek philosophy.

Continuing in the tradition of Classical philosophy, the general motion of the atmosphere was firmly believed to be in the same direction as Aristotle's first motion, and though Aristotle made only brief mention of currents in the Mediterranean, early Renaissance scholars took it as a simple matter of fact that the oceans should move from east to west. Where the water should go once it reached the western side of an ocean was an inevitable topic for debate. In the third decade of *De Orbe Novo Decades*, written in the year 1515 and published at Alcala in 1516, Peter Martyr discussed the opinions of contemporary scholars with regards to the issue. As translated by EDEN (1555, page 118), he said, "For wheras they al affyrme with on cusent, that the sea runneth there from the Easte to the west as swyftly as it were a ryuer faulinge from hyghe mountaynes, I thoughte it not good to lette' so great a matter slyppe untouched. The whiche while I consyder, I am drawen into no smaule ambyguitie and doute, whether those waters haue their course whiche flowe with so contynuall a tracte in circuite from the Easte, as thowghe they fledde to the west neuer to retourne, and yet neyther the weste thereby any whille the more fylled, nor the Easte emptied. If we shall saye that they faule to their centre (as is the nature of heuye thynges) and assigne the Equinoctiall lyne to be the centre (as summe affyrme) what centre shall we appointe to bee able to receaue so great aboundaunce of water?" In this way, an early question about the large-scale circulation was posed in terms of mass conservation, and Columbus' observations played no small role in it.

In Martyr's discourse, it is related that some people held the opinion of there being an outlet from the Atlantic to the Pacific somewhere between the Americas, but he was uncomfortable with this explanation because voyages to the region had not shown any evidence for it. Others contended that the American land mass was unbroken from the south to a mythical land beneath the ice of the

North Pole and that the water would have to flow north all along the coast to some unknown destination. Martyr was equally skeptical of this because his personal friend, Sebastian Cabot, who had just made a voyage in search of a northwest passage (around the year 1509), reported the occurrence of westward currents everywhere in the icy seas, though weaker than those the Spaniards had observed in the tropics. After describing the Venetian origins of Cabot's family and "the maner of the Venetians too leaue no parte of the worlde unsearched to obteyne richesse", Martyr continued: "He (Cabot) sayled lykewise in this tracte (the Canadian north) so farre toward the weste, that he had the Iland of Cuba his lefte hande in maner in the same degree of langitude. As he traueyled by the coastes of this greate lande (whiche he named Baccallaos – land of codfish) he sayeth that he found the like course of the waters toward the west, but the same to runne more softly and gentelly than the swifte waters whiche the Spanyardes found in their nauigations southeward. Wherefore, it is not onely more lyke to bee trewe, but ought also of necessitie to be concluded, that betwene both the landes hetherto unknowen, there shulde bee certeyne great open places whereby the waters shulde thus continually passe from the East into the Weste: which waters I suppose to bee dryuen about the globe of the earth by the uncessaunt mouynge and impulsion of the heauens: and not to bee swalowed up and cast owt ageyne by the breathynge of Demogoron (an infernal diety or magician regarded to be the genius of the Earth or underworld) as sume haue imagined bycause they see the seas by increase and decrease, to flowe and reflowe." As we discuss below, Martyr's belief in a large passage through the Canadian north, which was firmly rooted in Aristotelian philosophy, was used later by influential Britons to further their arguments for continuing their search for the northwest passage. Such a passage, the so-called Anian Strait, would provide a sea route to the riches of the Orient and it would not only be shorter than existing routes but would also be outside the realms of Spanish and Portuguese monopolistic control.

At the time of his writing, Martyr was unaware of the discovery of the Florida Current made just two years earlier in 1513 by Ponce de León. According to KOHL (1868), de León had sailed generally northward along the northeast side of the Bahama Islands and after reaching the northern end of the islands (~27°N) he turned toward the southeast, but was swept north by the current to around 29°N before reaching the Florida coast. He then sailed north to about 30°N before turning back toward the south, and by staying near the coast he unwittingly sailed with a southward countercurrent. An account of what followed on the 21st of April, 1513 was given by Antonio de Herrera in 1601 and translated into English by DAVIS (1935) with these words: "...all three vessels following the seacoast (southward), they saw such a (northward) current that, although they had a strong wind, they could not go forward, but rather backward, and it seemed that they were going on well; and finally it was seen that the current was so great it was more powerful than the wind. The two vessels that found themselves nearest the land anchored, but the current was so strong that the cables twisted; and the third vessel, which was a brigantine, which was farther out to sea, could find no bottom, or did not know of the current, and it was drawn away from land, and lost to their sight, though the day was clear with fair weather". This event occurred near a point of land jutting out from the coast, and because of the currents de León called it Cabo de las Corrientes; a few years later the Spanish renamed it Canaveral.

In the following years the Spanish established the continuity of land from North to South America, and by design their navigational routes came to follow the gyral pattern of surface currents in the subtropical North Atlantic. The southward Canary Current had long been known, the North Equatorial Current was immediately recognized by Columbus, and the Florida Current was equally obvious. By the year 1519 Spanish navigators were intentionally sailing along with the currents to America and northward along the American coast (HARRISSE, 1892; STOMMEL, 1950, 1965). Only the eastward flow of the northern limb of the subtropical gyre back toward Europe was not recognized. As we discuss in Section 2.3.3, the prevailing conviction of westward motion according to the *primum mobile* would not allow for such an admission.

2.3.2. Charts deriving from Sevillian cartography. Because the Florida Current was eminently clear to the first mariners who encountered it, and because it proved early on to be of great importance to navigation, one might expect pilot charts from the period of New World discoveries to show it in one way or another. Indirect evidence indicate this to be the case.

Seville, in southern Spain, served as a center for the accumulation of newly-discovered geographical knowledge. It was there that cartographers, geographers and historians could gain access to information brought back to Europe by the Spanish explorers. Produced from the pilot charts and navigational log books were maps of the New World, the earliest of which were often contradictory in important details. This prompted the Spanish government in the year 1508 to decree that an official map be created and that copies of it be easily obtained at a fixed low price. This map, the *Pardon Real*, was provided to pilots embarking for the New World, and these pilots were requested to mark on their map "every land, island, bay, harbour, and other things, new, and worthy of being noted"; and, as soon as they landed in Spain, to communicate their said chart, so annotated, to the Pilot-Major (HARRISSE, 1892). The *Pardon Real* was periodically updated according to the new information.

Manuscript maps, i.e., individually drawn and decorated charts, sometimes with highly ornate artwork, were constructed from copies of the *Pardon Real* for clients in cultured society. These maps were often drawn in the portolan style, as characterized by a system of lines radiating along the thirty-two points of the compass from one or more locations on the chart. Such lines were drawn on charts used at sea so that with a simple set of parallel rulers a course could be laid according to the wind. They were also included on the smaller and much more elegant manuscript maps, not out of any practical reason but rather as a matter of style in conformity with tradition. As the manuscript maps were custom-made articles not intended for scientific work, little or no explanation accompanied them; they often were not even signed or dated. Unfortunately, these seem to be the era's only maps that have survived to the present.

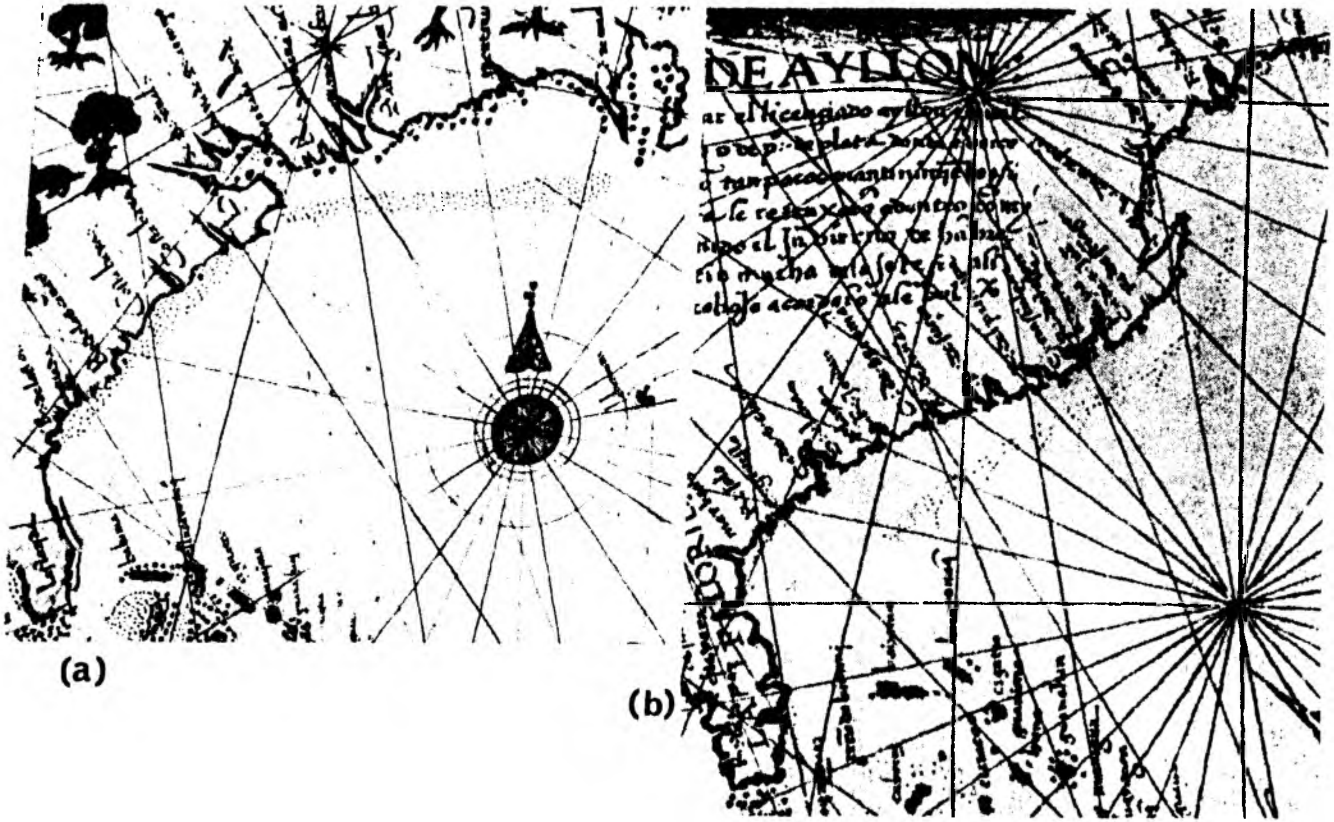
Early navigators were keenly interested in the accurate charting of potential dangers, such as reefs and other shallows, features that were plotted on pilot charts and similarly rendered on the manuscript maps. In the region of the Gulf Stream, an intriguing feature appears on the Salviati Planisphere Chart, produced for the powerful Florentine family of Salviati in about the year 1525 by Diogo Ribeiro (originally Diego Ribero, an instrument maker and pilot who served as the Portuguese Royal Cosmographer in Spanish Service from 1523 to 1530). Part of the Salviati Chart is reproduced in Fig. 1a, and on it is a narrow band of stippling that begins in the south at the coast near northern Florida and that follows the coastline of what represents North Carolina before turning off-shore after a short break toward the interior of the western North Atlantic. We have seen no discussion of this band presented in our source materials, and, in fact, it does not survive as a visible feature in many reproductions. Because the Gulf Stream had been observed quite far south of where the band begins and because the lower half of the band closely follows the coast, it is possible that the southern portion represents bottom shallows. But this seems unlikely because there exist no bottom features for navigators to be wary of in the northern portion of the band extending out to sea, and the competence of the Spanish pilots suggests they would not have made such an egregious error. Could it be that the Gulf Stream and its seaward turn were instead the features intended to be shown, just a dozen years after the discovery of the current? Although the depiction on the map is unimpressive by itself and is far from convincing in the absence of documentary evidence, the progression of how this band was later illustrated, combined with the Spanish use of the Gulf Stream in navigation, points to such a likelihood.

The most famed of Ribeiro's maps is his 1529 world chart, part of which is reproduced in Fig. 1b. As can be seen, the stippled band is now shifted off-shore, more in accordance with where the Gulf Stream actually is and where no shallow obstructions exist, though the band is now terminated off the Virginia - North Carolina coast without any seaward extension. Because the band has been moved away from the coast, from where caution of the bottom must be heeded and directly to where the Gulf Stream is found, one may surmise that the near-coast feature in the Salviati Chart represents a current that was marked on a pilot chart.

A subsequent map from the year 1534 (Fig.1c), by the Venetian historian and geographer Giovanni Battista Ramusio, shows the band in essentially the same place as in Ribeiro's 1529 map, but as a broader and much more prominent feature beginning just north of the Bahamas, where Ponce de León first discovered the current. Ramusio's woodcut *general map of the mainland and West Indies..., taken from two nautical charts made in Seville by the pilots of His Imperial Majesty* has at times been credited to Peter Martyr, as it was included in a 1534 edition of his *Decades*. As with the available descriptions of Ribeiro's charts, those we have seen of the Ramusio chart make little mention of the stippled band or of its significance. CUMMING, SKELTON and QUINN (1971) thought it represents dangerous shoals along a shallow coast, but this is inconsistent with the actual bottom bathymetry of the region that the Spaniards were routinely measuring.

One of the more prolific map-makers of the sixteenth century was a Genoese cartographer, Battista Agnese, who worked in Venice between 1536 and 1564. Little is known about Agnese himself, beyond that which appears on his maps, the artistic merits of which are now considered to be outstanding for the period (WAGNER, 1931). His maps show the stippled band, in much the same manner as Ramusio's. Agnese rarely dated or signed individual maps, as it was his practice to bind a small number of these individually-drawn charts, typically ten or eleven, into an atlas to be sold to a client. On occasion even the atlases were left undated. A portion of one of his charts of the North Atlantic is shown in Fig.1d, reproduced from a color facsimile appearing in the historical atlas of KUNSTMANN, SPRUNER and THOMAS (1859). According to KRUG (1901) the year of production of the original map was 1536; a detailed comparative analysis, however, of geographical names and outlines in Agnese's work (WAGNER, 1931) indicates that the actual date of production was most likely in the mid- to late-1540s. In the color facsimile, the band is yellow-green at its base near the Bahama Islands and gradually loses the yellow to become a more flat green at its northern terminus. Nowhere else on the chart is such a color scheme used, though many regions with navigational hazards are highlighted in other ways. KUNSTMANN, SPRUNER and THOMAS (1859) reproduced another chart from the same atlas, one extending from the eastern Indian Ocean across the Pacific and the Americas to the approximate longitude of Bermuda. The stippled band in the western Atlantic is shown on the second chart, with the same color scheme, along with a smaller, but similar feature in the western Pacific off the Chinese coast. Japan had yet to appear as an island on maps. It is tempting to think that the Kuroshio Current, long known to Japanese fishermen, was the feature intended to be illustrated in the Pacific. Agnese also drew oval maps of the world following the style of Ptolemy, and of the several we have seen, all show the stippled band off the American coast. This was a standard element included by Agnese on his maps during his working career of nearly thirty years.

As with the earlier charts shown in Fig.1, very little authoritative mention has been made of the meaning of the stippled band consistently and conspicuously depicted by Agnese. In the bibliography of her work on the cartographical history of ocean currents, KRUG (1901) noted that a certain Ernst Meyer (possibly a misspelling of the name Ernst Mayer, a contributor to the Austrian *Handbuch der Oceanographie* of 1883) thought this band, and the one in the Pacific, were intended to represent reefs, similar to the interpretation given by CUMMING, SKELTON and QUINN (1971)


DE AYLLON
(a)
(b)

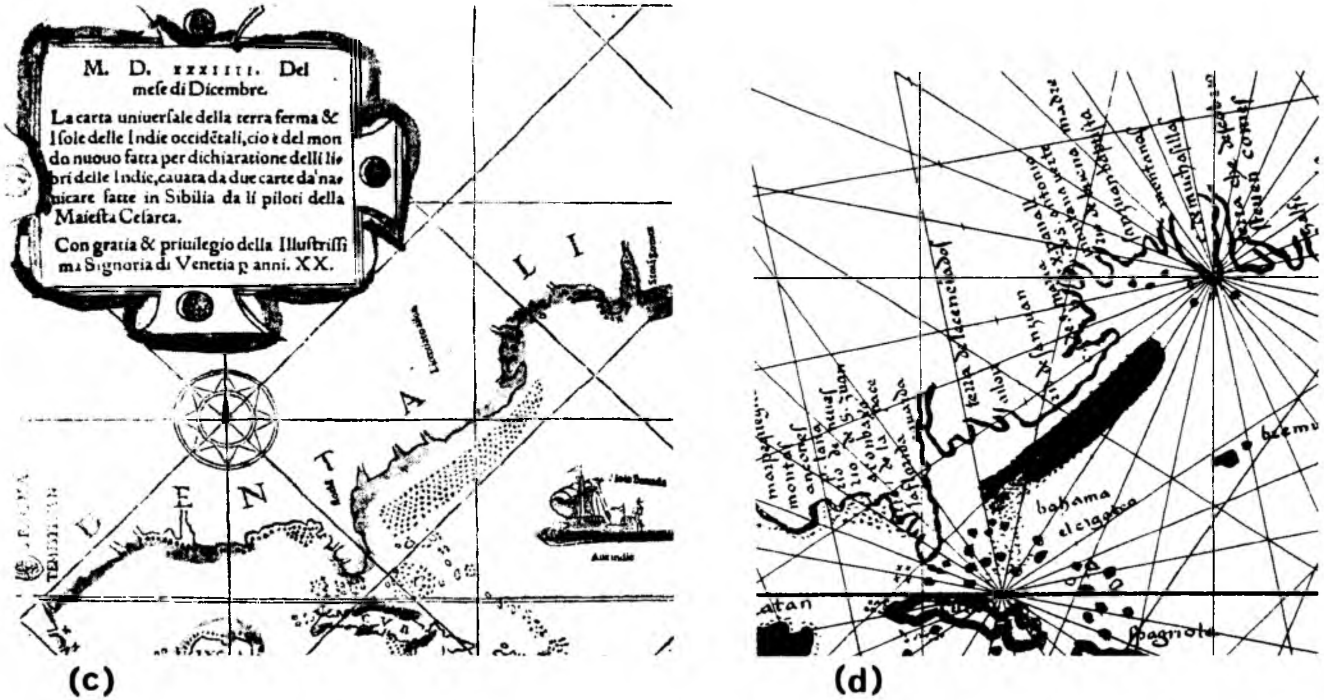


FIG.1. (a) Part of the Salviati Chart of 1525 by Diogo Ribeiro. (b) Part of the Ribeiro world chart of 1529. (c) Part of the Ramusio map of 1534. (d) Part of a map by Battista Agnese from the mid- to late-1540s.

about Ramusio's map. In the text accompanying the 1859 atlas, KUNSTMANN (1859) avoided mention of these features, discussing only the novel illustrations of the Strait of Magellan and Tierra del Fuego. Considering the geographical information gathered by the time of Agnese's maps, the care taken by Spanish navigators in sounding the bottom, their routine use of currents in navigation, and that there should be no more reason to erroneously draw reefs right in the regions of the two most important western boundary currents of the northern hemisphere as anywhere else, the probability is high that the Gulf Stream and Kuroshio Current were indeed the features intended to be depicted on the original pilot charts. It is curious, though, that this type of depiction by mapmakers in general appears to have ceased after the mid-sixteenth century. We have found no explanation for it – perhaps the original pilot charts were no longer being annotated with such a feature, or perhaps pilot charts were no longer serving as the mapmakers' primary sources of information.

2.3.3. Humphrey Gilbert; William Bourne. Once it was established that no passages connected the tropical Atlantic and Pacific oceans, the concept of a general westward oceanic motion imparted by the *primum mobile* had to be altered, though its importance as the central tenet remained firm. The North Equatorial Current of the Pacific Ocean was discovered in 1542 by Barnarde del la Torre, knowledge of which was combined with that of westward flows in the Indian Ocean, off the southern coast of Africa, and in the Atlantic to reinforce arguments for the ancient concept. This is evident from the opinions expressed by the British navigator Sir Humphrey Gilbert (1537-1583) in *A discourse of a discoverie for a new passage to Cataia*, first published in 1576. Gilbert's arguments were reprinted by the geographer and publicist Richard Hakluyt (1552-1616) in *The Principall Navigations, Voiages and Discoveries of the English Nation*, appearing in 1589. Like Gilbert, Hakluyt was a major proponent of the British search for a northern sea route to the Far East, and after the discovery of Hudson Bay in 1610 he helped establish the Northwest Passage Company of 1612. Gilbert concurred with several ideas conveyed by Peter Martyr six decades earlier, and still believing in the general westward motion he doubted the existence of the seaward extension of the Gulf Stream. Gilbert also provided an account of how the North Equatorial Current in the Pacific was discovered. From HAKLUYT (1589, pages 600-601) is the following from Gilbert:

"Also it (America) appeareth to be an Island, insomuch as the Sea runneth by nature circularly, from the East to the West, following the Diurnal motion of *Primum Mobile*, and carieth with it all inferiour bodies moueable, aswel celestial, as elementall: which motion of the waters, is most euidendtly seene in the Sea, which lyeth on the Southside of Afrik, where the currant that runneth from the East to the West, is so strong (by reason of such motion) that their Portingals in the voyages, Eastward to Callecute, in passing by Cap. De buona speranca, are enforced to make diuers courses, the currant there being so swift, as it striketh from thence, all along Westward upon the fret of Magellan, being distant from thence, neere the fourth part of the longitude of the earth: and not hauing free passage and entrance, thorow that fret towardes the West, by reason of the narrowness of the said straite of Magellan, it runneth to salue this wrong (Nature not yelding to accidental restraints) all along the Easterne coasts of America, Northwardes, so farre as Cap. Fredo, being the farthest knowen place of the same continent, towards the North: which is about, 4800. leagues, reconing there withal the trending of the land. So that this Currant, being continually mainteined with such force, as Iaques Cartier affirmeth it to be, who met with the same being at Baccallaos, as he sailed alongst the coastes of America, then, either it must of necessitie, haue way to passe from Cap Fredo, thorowe this frete, Westward towardes Cataia, being knowen to come so farre, onely to salue his former wrongs by the authoritie before named: or els it must needes strike ouer upon the coast of Island, Lappia, Finmarke, and Norway, (which are East from the said place, about 360. Leagues) with greater force, then it did from Cap. de buona Speranca, upon the fret of Magellan or from the frete of Magellan to Cap. Fredo, upon which coastes, Iaques Cartier mette with the same, considering the shortnesse of the Cut, from the saide C.Fredo, to Island, Lappia, &c. And so cause Efficient remaining, it would haue continually followed along our coasts, through the narrowe seas, which it doth not, but is disgested about the North of Labrador, by some through passage there, thorow this fret. ... So that it resteth not possible (so farre as my simple reason can comprehend) that this perpetuall currant, can by any meanes be maintained, but onely by continuall reaccesse of the same water, which passeth thorow the fret, and is brought about thither againe, by such Circular motion as aforesaid. And the certaine falling therof by this fret into Mare del Sure, is proued by the testimonie & experience, of Barnarde del la Torre, who was sent from P. del la Natiuidad to the Molluccf, Anno domini 1542, by commaundement of Anthonie Mendoza, then Viceroy of Noua Hispania, which Barnarde, sayled 750. Leagues, on the Nortthside of the Equator, and there met with a currant, which came from Northeast the which droue him back againe to Tidor. Wherefore, this currant being proued to come from C. de buona Speranca, to the fret of Magellan, and wanting sufficient entrance there, by narrowness of the straite, is by the necessitie of natures force, brought to Terra de Labrador, where Iacques Cartier met the same, and thence certainly knowen, not to strike ouer upon Island, Lappia, &c. and found by Barnard de la Torre, in Mare del Sur, on the backside of America, therefore this currant (hauing none other passage) must of necessity, fal out thorow this our fret into Mare del Sur, and so trending by the Molluccf, China, and C. De buona speranca, maintaineth it selfe by circular motion, which is all one in nature, with Motus ab Oriente in Occidentem."

Gilbert's argument for the existence of a Northwest Passage rested upon a continual northward flow existing all along the coasts of South and North America, but he did not address the question as to why the northward flow off Florida should be so uniquely strong. Other writers did, one of whom was the Cosmographer to King Henry III of France, Andre Thevet (1502-1590). In his *La Cosmographie Universelle*, THEVET (1575) discussed prevailing theories, including ideas that the westward flow in lower latitudes strikes land at its highest point before turning north as a strong downhill-running current (a theory that would be repeated in various forms into the early twentieth century), and that a constriction between the Florida coast and submarine mountains might lead to the strong current; his own suggestion was that freshwater discharge by the Mississippi into the Gulf of Mexico was the cause (BURSTYN, 1971).

Gilbert's argument also rested upon no eastward flow occurring in the northern North Atlantic. Richard Willes advised the same (HAKLUYT, 1589, page 615) before the navigator Sir Martin Frobisher (1539-1594) set sail in 1576 on his first voyage to find the Northwest Passage. But according to Dionise Settle (HAKLUYT, 1589, page 623), when Frobisher was crossing the North Atlantic in 1577 on his second voyage his company observed evidence for the North Atlantic Current: "All along the seas, after we five daies sailing from Orkney, we met floting in the Sea, great Firre trees, which as we iudged, were with the furie of great floods rooted up, and so driuen into the sea. Island hath almost no other wood nor fuell, but such as they take by uppon their coastes. It seemeth, that these trees are driuen from some part of the New foundlande, with the current setteth from the West to the East."

Most of the discussions taking place about what might be were, in essence, out of the reach of laymen; books were being written by scholars, for scholars, most often in Latin. In a break with this long-standing tradition, a middle-class British innkeeper by the name of William Bourne (?1535-1582), who had a knowledge of mathematics and geometry and interests in the sea and navigation, wrote in English a general book for popular reading that presented the basic concepts of navigation then known, along with explanations of the physical processes at work in and near the seas. This book, *A booke called the Treasure for Traveilers, deuided into fiue Bookes...* was published in 1578. In his fifth book (chapter), Bourne (1578) spoke of the Moon as being moved by the *primum mobile*, but he also described the Moon as having some unknown power that was responsible for the tides and steady currents (the concept of gravity was still several decades away). He envisaged a landless Earth covered with water in which an elevation of water would move from east to west beneath the Moon (an idea similar to that used in the modern equilibrium tide model), but that the disrupting presence of land masses acts to complicate both the tides and steady currents.

For the steady currents, Bourne (1578, fifth book, page 13) described a system in which the principal westward motion at the southern end of Africa merged with that of the central Atlantic into a movement of water too great to be admitted through the Strait of Magellan: some went through the strait into the Pacific while the rest had to be diverted northward along the east coast of South America, into the Gulf of Mexico, but then eastward with the current between Florida and Cuba back toward Europe. Bourne (1578) had thus come somewhat close to describing a gyral pattern in the North Atlantic, but oddly enough, he made no mention of the northward Florida Current, and like Gilbert, he had the flow along the southern coast of Brazil as going the wrong way. He also speculated that the southernmost part of the flow coming from the Indian Ocean would meet with Tierra del Fuego, still thought to be a part of an unseen southern continent, and would be deflected back toward the east along the coast of the southern continent and ultimately back into the Pacific. Finally, Bourne proposed that a second type of general, non-tidal current exists, one that flows against the wind during periods of strong winds. His rationale was that the action of the waves would create an upward tilt of the sea surface downwind, which would then make the water run back against the wind in order for the sea to remain as level as possible.

The pervasiveness of the belief in a general westward motion caused serious doubt to be cast upon reliable observations of currents flowing toward the east, particularly in the low latitudes where westward motion had been the most striking. An example is the British observation of the Equatorial Countercurrent / Guinea Current during an unsuccessful attempt to circumnavigate the world by Captain Fenton. On July 23, 1582, he had an anchor lowered to the sea floor off the western coast of Africa in about 700 meters of water, and there he discovered his ship was being set strongly to the east by an unexpected current; his finding was not well received by contemporary geographers (Taylor, 1959).

According to Bourne (1580), what we now call the Labrador Current had already been encountered by Frobisher when he saw icebergs floating south and then stayed by the Gulf Stream. The Labrador Current was again observed by Sir Humphrey Gilbert during his voyage of 1583. As written by M. Edward Haies (Hakluyt, 1589, page 685), "Saturday the 27 of July, we might descry not farre from us, as it were, mountaines of ise driuen upon the sea, being then in 50 degrees, which were carried Southward to the weather of us: whereby may be coniectured that some currant doth set that way from the North." Also, following the narrative of the 1586 voyage of the Earle of Cumberland, a voyage intended for the South Sea but reaching no farther south than 44°S along South America, the Brazil Current off present-day Salvador was mentioned in a short passage (Hakluyt, 1589, page 805): "If you goe out of Bayea, for the northward, you must hall off east, and by north, till you be 30. or 40. leagues off from the currant."

2.4. Late Renaissance – generalizations of the system

Despite the wealth of new information about ocean currents gathered by mariners during the first century of discoveries, a few still refused to believe that the ocean could circulate at all. One was the Spanish Jesuit priest José de Acosta (1539?-1600), who expressed his views in his *Historia* *natural y moral de las Indias.* In it, ACOSTA (1590) discussed the westward motion of winds in the lower latitudes in the usual Aristotelian manner while saying that the eastward winds in higher latitudes were simply countercurrents set up by the former. However, because of land barriers he contended that no continuous westward current exists in the ocean, and by implication, no general circulation (BURSTYN, 1971). Such a cavalier attitude toward observational evidence, though, was becoming increasingly anomalous. Following the invention of the telescope and with the growing acceptance among scholars of the heliocentric theory of Copernicus (1473-1543), the long-standing Greek ideas of universal westward motion finally began to erode, albeit slowly. Individuals such as Galileo (1564-1642) and Kepler (1571-1630) did not dispute the generality of westward motion at low latitudes, but they attributed it to the atmosphere and oceans there not being able to keep up with the rotation of Earth.

2.4.1. Bernhard Varen. The theory of Galileo and Kepler was just one among many being offered. The concepts and state of knowledge about the sea, as they stood in the mid-seventeenth century, were summarized in the widely cited book, *Geographia Generalis.* It was written by Bernhard Varen (1622-1650?), a German physician living in Holland who is commonly accredited with being the founder of modern general geography. *Geographia Generalis* was published at about the time of Varen's early death, and it proved to be one of the most important works of the baroque period. It was the first comprehensive, objective assemblage of geographical knowledge since the Greek Classical Age, reflecting the atmosphere of empiricism that was growing in the Renaissance. Not being an experimental scientist himself, however, VARENIUS (1650) at times fell back on fables and speculation as writers in the past had done, thus giving rise to a mix of objectivity and fantasy, though he must have considered everything he said to be factual.

Varen's work drew the acclaim of, among others, Sir Isaac Newton (1642-1727), who was more cautious when it came to untested, or untestable theories and unsubstantiated observations. Newton edited the treatise by VARENIUS (1650), with the first edited volume coming out, in Latin, in the year 1672 and the second in 1681. Newton's Latin version of *Geographia Generalis* was subsequently translated into English under the title, *A Compleat System of General Geography,* which has since become the most widely read rendition of Varen's work. In a 1736 version of *A Compleat System* is a comment by the editor that reads, "The Reason why this great Man (Isaac Newton) took so much Care in Correcting and Publishing our Author, was, because he thought him necessary to be read by his Audience, the Young Gentlemen of Cambridge, while he was delivering Lectures upon the same Subject from the Lucasian Chair".

We are unaware of previous discussions of how Newton edited VARENIUS' (1650) original work. To learn more about this, we have located a more rare English translation of *Geographia Generalis* that was published in the year 1683 (possibly for the first time in 1680) under the title *Cosmography and Geography.* According to remarks on the title page it appears to be a straightforward translation with no attempt to edit or correct Varen's statements. The differences between this version and *A Compleat System* lie not in its organization, as the order of materials presented is the same, but in the use of a less antiquated English in the latter together with qualifications made by Newton to Varen's text that make the narrative much less speculative. Here we draw mainly from *Cosmography and Geography* because it most accurately reflects Varen's own thinking, and because it was written in a style closer to that which would have been used had *Geographia Generalis* been originally penned in English.

Varen described the global water balance in terms of the ocean occupying the "Cavities of the Earth," depressions on the solid Earth he thought could not far exceed a German mile, or 4800m. This idea probably derived from the ancient concept of equilibrium in which the oceans were thought to be about as deep as the mountains are high. Rivers, Varen thought, are fed from the ocean through a network of subterranean passages (deriving from Socrates) and through rains resulting from evaporation of sea-water.

More pertinent are the ways Varen categorized the motions of the sea and his comments regarding the importance of wind. He wrote that the motions of the sea include a continuous westward flow most strongly observed in the tropics, the periodic flux and reflux of the sea, and special flows including what we now call the Florida Current, the Kuroshio Current, the Peru Current, the Mozambique Current, and the strong, particularly perplexing, eastward flow of the Guinea Current (which he supposed could possibly be the result of the sea falling into a subterranean channel in the Gulf of Guinea). None of these currents, however, nor any other, were referred to by specific names; they were identified solely on the basis of location and direction of flow.

Varen considered the general westward flow to be the fundamental steady motion in the ocean, upon which motions caused by winds were superimposed to one degree or another. Unsteady winds would lead to unsteady, short-lived currents, whereas more persistent winds would cause permanent alterations to the general westward motion, such as the steady northward flow of the Peru Current. Of this he said, "The fourth special perpetual motion is in the Pacifick Ocean on the Coast of Peru, and the rest of America, where the Sea is moved from the South to the North: questionless the cause is a perpetual South wind; which is found to predominate on those Coasts, as we have shewed in our Chapter of Winds. In the Sea remote from the Coasts this motion is not discovered, neither this wind."

Varen discussed the various contemporary theories regarding the seas' motions, with those for the general westward motion including a magnetic pull from the Moon, thermal expansion as a result of moonlight, pressure transmitted downward from the Moon through an endless atmosphere, the Sun somehow pulling the water along after it, the inability of the sea to keep up with the Earth's rotation, and so on. His own conclusion was that the cause was uncertain, though he showed more favor with the idea that the general westward currents in the tropics were because of the prevailing winds, as were all other non-tidal currents. He also discussed the possible mechanisms for tides, saying only that the Moon was responsible in a way as yet unknown. Kepler had already applied the relatively new concept of gravitational attraction to the tidal problem, but it was not yet widely discussed and would not be until Newton solved the problem in 1687.

Varen's statements about the steady currents being driven by wind are the earliest we have found to explicitly make this fundamental connection, though he undoubtedly became aware of the argument through existing sources. In 1604, Francis Bacon (1561-1626) contended that currents in the sea are influenced by periodic winds (BURSTYN, 1971). Newton apparently approved of Varen's opinion in this case, as he made no alterations to it. Oceanic motion was finally being considered in terms other than the *primum mobile*. Other essential generalities passed on by Varen are that "The Water of the Ocean becometh less salt by how much it is nearer the Poles; and on the contrary, the more salt, by how much it is more near the Aequator or Torrid Zone," and that "Sea-Water is more ponderous than fresh water, and the water of one Sea is more heavy than another". He discussed various reasons for inequalities in surface salinity, including evaporation and precipitation, though the effects of variations in density on circulation were not suspected.

For the novel and essentially correct concepts that Varen discussed, he erred in reporting certain other phenomena. The role Varen assigned to the ancient concept of subterranean channels in the hydrologic cycle was complete fantasy, but he argued strongly for the case (modified by Newton to become only an outside consideration). The global water balance had been and was continuing to be a topic for debate, but it drew little attention from the small community of observational scientists. HALLEY (1693) made one of the most notable of the early inquiries into this, but only in a heuristic way when he addressed the question of how the level of the sea remains constant in view of the large losses through evaporation and the seemingly slight amount of river drainage. Halley explained for perhaps the first time that moist air from the sea is lifted by mountains, leading to precipitation at high elevations from which streams and rivers are formed, while the rest of the evaporated sea-water is returned directly through precipitation over the ocean.

Varen erred again when he included, as observational facts, accounts of immense whirlpools. Short-lived vortices on the order of meters across can be produced in a small number of coastal locations having large tidal ranges and conducive local currents. Sensationalized from the outset, stories about them were repeated with such enthusiasm that whirlpools came to be widely regarded as important to the workings of the ocean. DEACON (1971, pg. 24) supposed that Paul the Deacon (720-778 A.D.) was the inventor of the theory that tides were caused by whirlpools alternately sucking in the sea and spewing it out again. This myth, ostensibly flavored by Homer's description of Charybdis, descended through time and, in a variation, Varen reported on the famous Lofoten Maelström (or Moskenström) as: "The vortex at Norway is the most noted and greatest of all, for it is related to be 13 miles in circuit (about 90km using the Norwegian mile, 60km using the German mile); in the middle of it is a Rock called Mouske. This Vorago in fixed hours sucketh in all that approacheth near it; as Water, Whales, laden Ships, and in so many hours vomiteth them all out again with a great violence, noise, and circumgyration of water. The cause is unknown." (The term Maelström is probably of Dutch origin, from *malen*, meaning to grind or whirl, and was applied to a strong current running past the southern end of the Island of Moskenaes, a member of the group of Lofoten Islands off the northwest coast of Norway; a vortex is frequently associated with it, one that has been shown on several maps, even in Mercator's Atlas of 1595.) Varen was convinced of the existence of great whirlpools, but Newton was skeptical and retained only passing reference to them in his edited version.

2.4.2. Isaac Vos. The next step toward a better understanding of ocean circulation was to view prevailing local surface currents as part of a larger system. This was taken in 1663 by Isaac Vos (1618-1689) in de *Motu Marium et Ventorum Liber* (translated into English in 1677 as *A Treatise Concerning the Motion of the Seas and Winds*, recently reproduced by DEACON (1993a)). Vos was the son of a renowned Dutch-Humanist theologian involved with the Reformation, himself becoming an eminent classical and ecclestiastical historian. He served in the court of Christina of Sweden, until 1673 when he was appointed resident canon of Windsor. Having a progressive outlook, he was inclined toward trying to understand observations of nature with secular explanations.

In *de Motu Marium*, VOSSIUS (1663) built up a scheme of ocean circulation beginning with the westward flow in the tropics (described as shifting north and south with the seasonal declination of the Sun) which would flow around the Earth were it not for the obstructions presented by land. Like Varen, Vos thought all other currents were caused by the tropical flow and the existence of continental land masses. Using an argument based essentially on conservation of volume, Vos traced the known flow patterns into a closed anticyclonic circulation cell in each of the subtropical ocean basins. Taking the Atlantic as an example (his pages 24-25), he described how the flow coming from Africa toward America splits near Brazil and sets up a circular system in each hemisphere. Once the current has split, the northern branch carries water into the southern Gulf of Mexico and then back out between Florida and Cuba before continuing on as a strong northward current along the eastern coast of North America, where a part of it then flows directly east toward Europe and finally south toward Africa to replace the waters driven west. He described a similar circular pattern, rotating in an anticlockwise direction, in the South Atlantic, and he argued that the North and South Pacific and the Indian Ocean all have corresponding systems of circulation as well, though the monsoonal cycle in the northern Indian Ocean gave Vos no small amount of difficulty.

The subtropical gyres were at last explicitly described, which proved to be Vos's principal contribution toward improving the picture of ocean circulation. Unlike Varen, who thought wind was the most likely cause of surface currents, Vos placed little importance on it. Instead, he contended that solar heating produces an oceanic elevation beneath and trailing the Sun that forces water to rush downhill in advance of the Sun's motion. He thought this was the universal motion of the sea, though less noticeable in extra-tropical locations away from the Sun's footprint. The eastward flows in mid-latitudes, he maintained, were coexistent with weaker westward components, arguing at some length that opposing currents can meet, pass through each other, and be individually sustained. As a supporting analogy, he cited the way opposing surface waves can pass through one another and remain intact. Vos formulated other theories we now dismiss, including several about tides.

2.4.3. Athanasius Kircher; Eberhard Happel. Vos's descriptions of closed subtropical gyres do not appear to have made much impact upon other writers who soon followed; sentiments during the Counter Reformation may have been an underlying factor. The types of motion in the sea outlined by Varen, however, received considerably more attention. They were widely accepted and repeated by less specialized encyclopedia writers, and by respected authorities such as Isaac Newton, though Varen's undogmatic manner of thinking was not necessarily emulated. Concessions to the Copernican helio-centric arrangement of the universe were inadmissible to Catholicism during the Counter Reformation, as were the newly developing modern concepts of gravitation. Writers of general science who embraced mainstream theology were consequently obliged to try to make order out of a growing wealth of observations of natural phenomena with ancient concepts. The first maps of the global ocean circulation were made by such writers, and the features depicted on their maps more closely reflect the ideas of Socrates and Aristotle than they do the knowledge available in the middle of the seventeenth century.

The earliest chart of the global ocean circulation appeared in the encyclopedic work of the Jesuit priest Athanasius Kircher (1602-1680), *Mundus Subteranneus*, first published in the years 1664/5. Kircher received his education in Germany, and then settled in Rome in 1634 where he began a career of assembling and disseminating knowledge over a broad spectrum of subject matters. He was a prolific writer with a strong sense of curiosity, but was limited in his interpretations by mystical conceptions of natural laws and forces. These qualities are manifest in his chart of ocean circulation (Fig.2, reproduced from the third edition of 1678, which is identical to that in KIRCHERI (1664/5) but mounted in such a way that it can be folded out flat). Kircher firmly believed in Aristotle's theory of the *primum mobile*, and in his map the general westward flow thought to result from it nearly fills the Pacific and occupies much of the Indian Ocean, but is shown in just parts of the Atlantic, the much better known ocean. Within the South Atlantic, a closed subtropical gyre is shown whose westward flow near the equator splits at the eastern promontory of Brazil, with the northern branch continuing along northern South America into the Gulf of Mexico, where it makes an anticyclonic loop paralleling the coast. The lines of flow exit the Gulf of Mexico north of Cuba and turn sharply northward along the coast of Florida to join with other flow sweeping north and northeast to the region north of Scandinavia, the reason for which comes shortly. No closed circulation in the North Atlantic is shown as would be expected had Kircher used the observational information available at the time and the descriptions given by Varen and Vos. The other branch of flow split by the Brazilian promontory is shown as feeding both a recirculation of a gyre in the South Atlantic and a branch moving south all the way to the Strait of Magellan before continuing west into the South Pacific. The South Atlantic is the best-depicted ocean by Kircher,

FIG.2. World chart of ocean currents from *Mundus Subterraneus* (KIRCHERI, 1664/5).

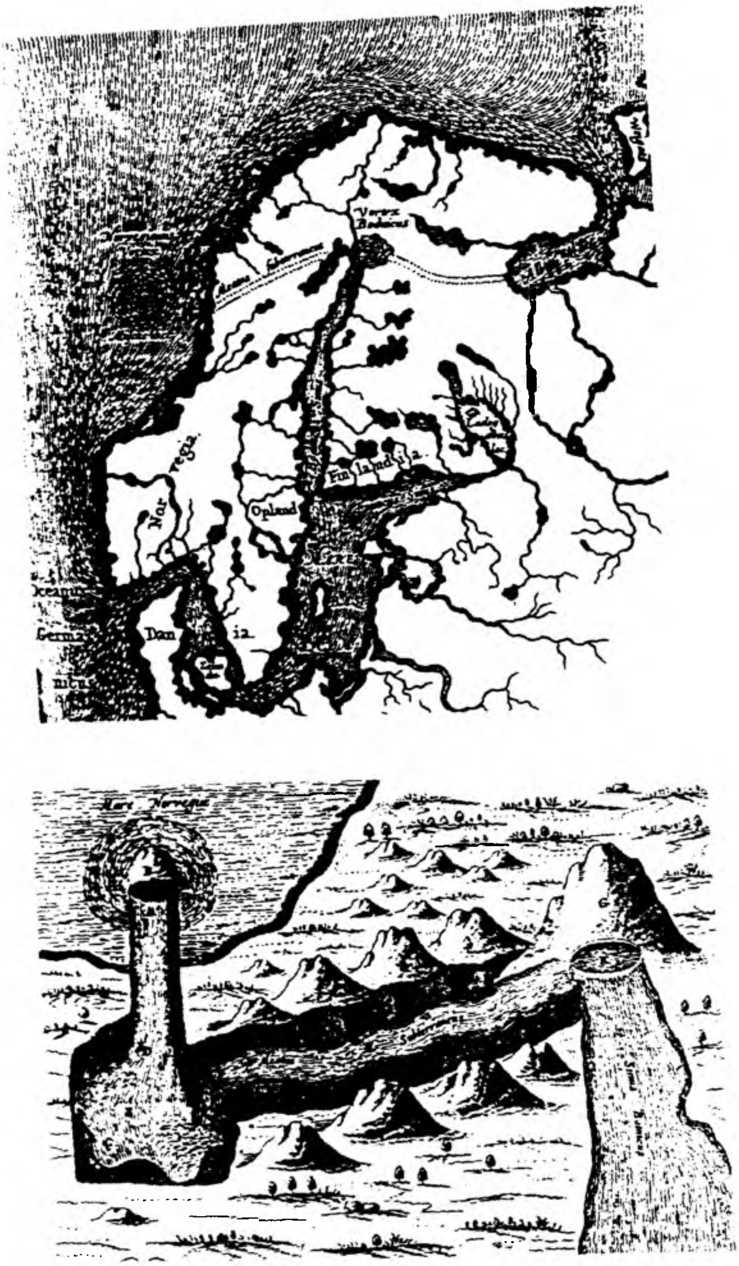


FIG.3. (a) (upper). Depiction of the Maelström off the northwest coast of Norway. Dashed lines indicate supposed subterranean channels connecting the vortex with the Gulf of Bothnia and Barent's Sea. From *Mundus Subterraneus* (KIRCHERI, 1664/5). (b) (lower). Detail of the supposed connection between the Norwegian Maelström and the Gulf of Bothnia depicted in Figure 3(a). From *Mundus Subterraneus* (KIRCHERI, 1664/5).

but his sketchy narrative suggests that the features were drawn as much out of imagination as from evidence.

The south polar continent shown on Kircher's map had not yet been seen; it was drawn in the long tradition passed down through the literature following its speculative introduction by Hipparchus in 150 B.C. and called *Terra Incognita* by Ptolemy in 150 AD. It would not be removed from the charts of navigators until after James Cook completed his second voyage (1772-1775), a circumnavigation of the Southern Ocean, without sighting land (though Cook continued to believe in a southern land mass, mainly because of the large icebergs which he thought must originate from land).

Other features to note on Kircher's map are the small spots. These were intended to show the supposed locations of whirlpools and entrances to a vast system of subterranean channels, many of which he described in detail and which inspired the title of his book. Homer's Charybdis was assumed to be in the Strait of Messina, so Kircher showed a whirlpool there. He also illustrated an opening to the channel in the Gulf of Guinea that Varen thought might possibly exist, along with many other channel entrances. In some places channels are shown that link these entrances, for example the pair of dots straddling the isthmus of Panama which Kircher said would facilitate the general westward motion. Further pairs show supposed connections between the Caspian Sea and Persian Gulf, and between the Mediterranean and Red Sea along the line of the present-day Suez Canal. Kircher misplaced the Norwegian Maelström on this map, but he provided a more accurate location (Fig.3a) as part of a more detailed discussion of the feature (including much of what Varen had said about it) and its supposed connection with the Gulf of Bothnia by way of a subterranean channel (Fig.3b).

A vexing phenomenon to explain in terms other than gravity was that of tides. To Kircher, the answer to this problem, and to why various currents should deviate from the ideal motion imparted by the *primum mobile*, rested in a furthering of the idea of subterranean channels and cavities. He imagined Earth as rhythmically sucking water into its interior through the North Pole (thus explaining the general pattern in the North Atlantic portion of his global map) and reissuing it through the South Pole. This explanation likely derived from a theory given by Merula in 1605 which said that ships sailing to the North Pole would never return because water was drawn together there and pulled into the Earth (KOHL, 1868). The ejection from the South Pole, according to Kircher, took place mainly within the three sets of lines shown on the map that radiate from the southern continent into the Indian Ocean, with each set leading toward an entrance to a subterranean channel. We do not know Kircher's reason for the pattern, but the illustration of a set of lines passing each side of Kerguelan suggests that a sea captain or two had reported unusually large ship drifts toward the north, a bias that could easily result from undersampling in this region which is now known to be characterized by a unique confluence of meandering ocean fronts and current cores (PARK, GAMBERONI and CHARRIAUD, 1991; BELKIN and GORDON, 1996).

The intensely speculative nature of Kircher's work reflects not only his own vivid imagination, but also the difficulties faced by a conservative clergy that continued to adhere to classical Greek ideas during a time of rapidly expanding knowledge and transition toward empiricism. It also highlights the awe with which people viewed the mysteries of the sea.

Kircher's volume on the oceans inspired the German writer of epics, romance and adventure, Eberhard Happel (1647-1690), to venture into geographical matters by publishing in the year 1685 the mystical volume, *Gröste Denkwürdigkeiten der Welt oder Sogenannte Relationes Curiosae*. It contains descriptions and a chart of ocean currents (Fig.4), the second ever to depict the global circulation. Many of the patterns and features from Kircher's map appear in this one, and descriptions in the text are similar as well. Like Kircher, HAPPEL (1685) argued against the idea


Grün=Landt
California
A
M
C
I
Neü=Holland
Virginia
Brasilien
Der Verſchlingende Moſkoe-Strohm
Das feſte Land Norwegen

FIG.4. World chart of ocean currents, with an illustration of the Norwegian Maelström (inset), from *Relationes Curiosae* (HAPPEL, 1685).

of the Moon causing tides, a theory, he said, that was being vainly pursued in Britain. He also assumed the existence of a vast reservoir beneath each polar region, but that each took in water at special hours and discharged it at others; he maintained this was a much better explanation than Kircher's where water was thought to flow into just the North Pole and out the South. Also like Kircher, Happel embellished certain myths surrounding whirlpools (his drawing of the Maelström is shown in the inset in Fig.4), and he furthermore passed on descriptions of imaginary sea creatures and mermaids (allegedly given to him first-hand by sea captains).

These explanations did not escape occasional criticism, but because none of the era's few experimental scientists focused on the sea's circulation such ideas were allowed to become entrenched in popular thinking, and they remained in the mainstream literature for many years to follow. Other works from the seventeenth century gave similar accounts of channels and reservoirs in Earth's interior, such as those by FOURNIER (1667) and WOODWARD (1695), while in the eighteenth century Kircher was still cited as an authority on oceanic motion and the Norwegian Maelström (e.g., the lexicon by ZEDLER, 1739) and the idea of water circulating deep within the Earth remained acceptable (e.g., MEAD, 1758). In the nineteenth century the Maelström and other whirlpools continued to receive entries in geographical encyclopedias (e.g., MURRAY, 1834) and in the respected *Encyclopaedia Britannica* (6th edition, 1836), though in more factual terms. Edgar Allen Poe drew information from the latter (MABBOTT, 1978), and from Kircher, for his celebrated tale published in 1841, *A Descent into the Maelström*. The description of the vortex given by the old Norwegian fisherman in the tale closely resembles that written by Varen, which in turn mirrors that of Charybdis as told by Homer. So in an innocuous way, this bit of fantasy conceived in the Mediterranean Bronze Age has survived into our own culture.

The first global charts of currents appeared shortly before the tidal question was resolved by NEWTON (1687) in *Philosophiae naturalis principia mathematica*, and though his theories on tides did not gain easy acceptance (DEACON, 1971) it is clear that the understanding of tides was at a much more advanced state than was that for currents in general. In the same year that Newton's work appeared, HALLEY (1687) made the first step toward giving a satisfactory explanation of the trade winds, i.e., that they result from differences in temperature and thus density and pressure, but he also thought the least dense air, and thus lower pressure, was to be found under the Sun as Earth rotates beneath, thereby causing the general tendency of tropical air to be toward the west. He made no mention of ocean currents, as these were not yet topics of inquiry for the small community of observational scientists. Instead, the compilation of facts regarding currents, as before, was done by seafarers alone in the interests of safely executing long voyages. As they had done in previous centuries, ship operators kept detailed records of the geographic, hydrographic, and weather conditions with which they met, and these records were the foundations for sailing directions that were first published in the sixteenth century and then enlarged upon in the seventeenth.

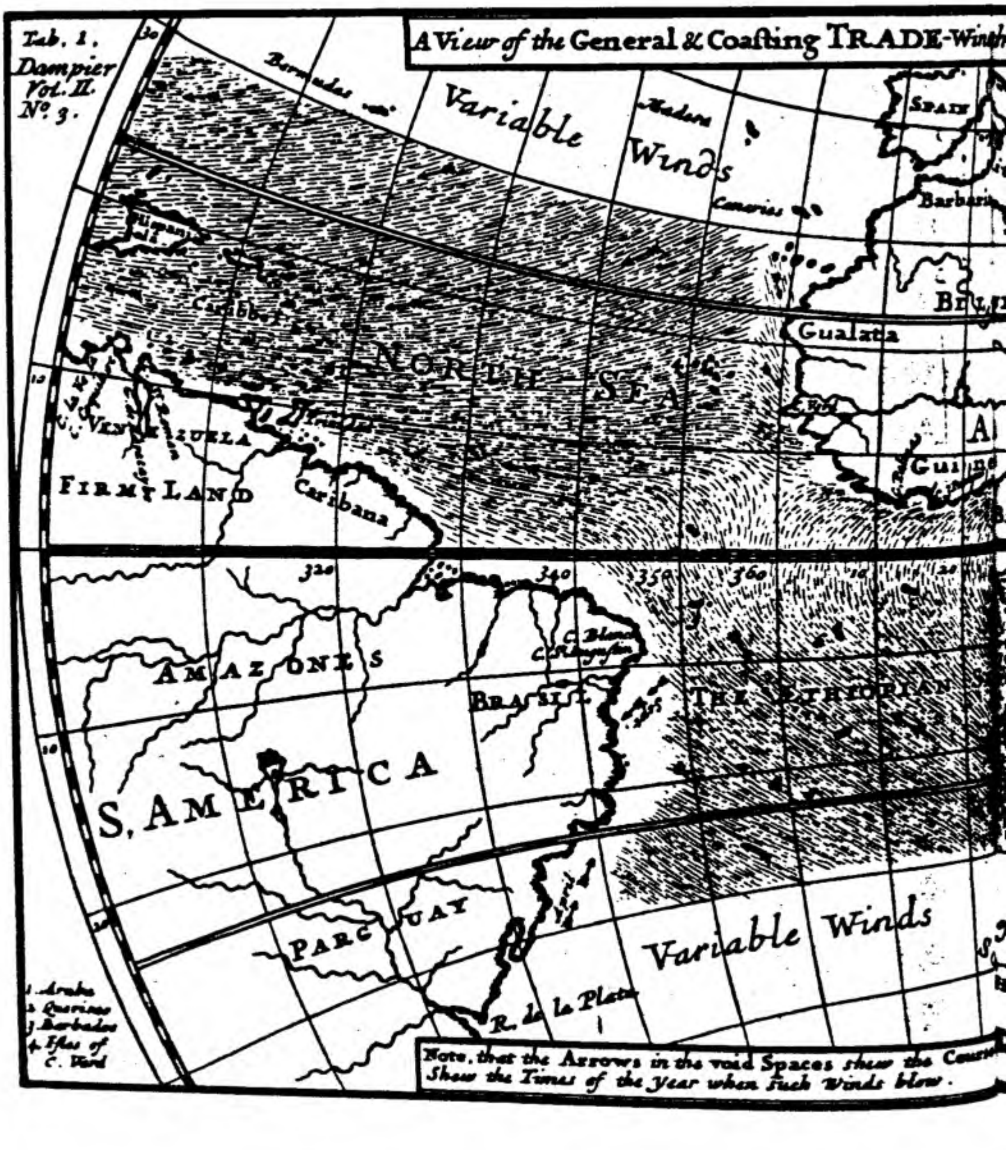
2.4.4. Count Marsigli. In the 6th century the Byzantine historian Procopius of Caesarea noted a belief among local fishermen in the undercurrent of the Bosporus Strait (DEWING, 1928), and by the middle of the seventeenth century mariners knew about an undercurrent in the Kattegat (strait between Denmark and Sweden). And though it had yet to be observed, the subsurface outflow from the Mediterranean to the Atlantic had been speculated upon as early as 1661 as an explanation for the seeming excess amount of water entering that sea (see DEACON, 1971). Other than regional instances such as these, however, and the vague notions of subterranean channels connecting the sea with Earth's interior, little serious thought seems to have been given to the possibility of large-scale flows of water at depth in the open ocean. In fact, a common method for measuring currents in calm weather was to lower a weight on a line that would act as a sea anchor, and this rested upon the assumption of deep stillness. In 1671 Robert Boyle (1627-1691) wrote of evidence for the ocean's deep water being everywhere cold, and he further suggested that the ocean can be divided into two regimes – a surface region warmed by the rays of the Sun and a deeper region where the natural coldness of water prevails (DEACON, 1971; MCCONNELL, 1982). In 1691 Robert Hooke (1635-1703) considered such an arrangement as being statically stable, with the warm, less dense water overlying the heavier colder water, and that heating from the Sun should not be expected to extend to any considerable depth (DEACON, 1971).

The experimental method, as employed by Galileo and a few others, impressed a young Luigi Ferdinando Marsigli (1658-1730), who was born into a noble family in Bologna, Italy and was provided the means to travel while pursuing his studies (OLSON and OLSON, 1958; DEACON, 1971; MCCONNELL, 1982). Count Marsigli had many interests, important among them being the physical and biological conditions of the sea. He was in Constantinople in 1679 on diplomatic service when he learned of the undercurrent in the Bosporus Strait from local fishermen and the British ambassador, and he became perplexed. Not willing to simply accept the stories, Marsigli went about to make measurements of his own. He constructed a current meter having a wooden propeller for measuring the flow at the surface, and he could observe the change in current direction with depth through the use of a rope onto which were tied pieces of white-painted cork. As an explanation for this intriguing phenomenon, Marsigli hypothesized that the great evaporation over the Mediterranean caused its waters to be saltier, and thus more dense, than the Black Sea water, and this would drive a surface flow from the Black Sea to the Mediterranean and a subsurface return flow. He obtained water samples and allowed equal volumes of them to evaporate, and the weights of the residuals confirmed the higher salinity of the Mediterranean. Then he demonstrated the validity of his rationale with a tank experiment.

Marsigli's study was published in Rome in 1681 as a tribute to Christina, former Queen of Sweden. The following year Marsigli joined the Austrian military in its fight against the Turks, and he was soon made a commander. For much of the remainder of his life he engaged in military and diplomatic efforts, for which he became well known; throughout his career he also continued to conduct scientific investigations whenever he could. In 1725 he published the text *Histoire physique de la Mer*, which was written mainly on the work he conducted while staying at Cassis, France in 1705-1706. Unfortunately, the fame he enjoyed as a public servant did not translate into recognition for his scientific works, perhaps because he interacted little with the scientific community (OLSON and OLSON, 1958). His 1681 study of the Bosporus reached England by 1684 and was apparently known to Robert Hooke (DEACON, 1971), but his ideas about the effects of density differences on water motion were not adopted in the controversy surrounding the analogous problem with flow through the Strait of Gibraltar, nor were they thought of in terms of the general oceanic circulation. The earliest discussion of this would have to wait until 1755, again in an obscure publication (Section 2.5.4).

2.4.5. William Dampier. By the late 1600s the most comprehensive sailing directions were published by the Dutch, but they contained no directions for ports outside Europe and no instructions for open-ocean passages (BELL, 1931). Addressing this issue, William Dampier (1652-1715) published in the year 1699 his *Discourse of the Trade-Winds, Breezes, Storms, Seasons of the Year, Tides and Currents of the Torrid Zone throughout the World.* It was written largely on the basis of his own observations.

In brief, Dampier sailed from England to Jamaica in 1679, his second such voyage, in the hope of finding success in the lumber trade. He maintained a detailed travel diary of events, a practice he had begun on his first voyage. However, after arriving in Jamaica he changed plans, and was about to return to England when he took up an offer for a short voyage to the Mosquito coast. A stop was made along the way in western Jamaica, at Nigril Bay, where a fleet of British and French


Tab. 1.
Dampier
Vol. II.
No. 3.
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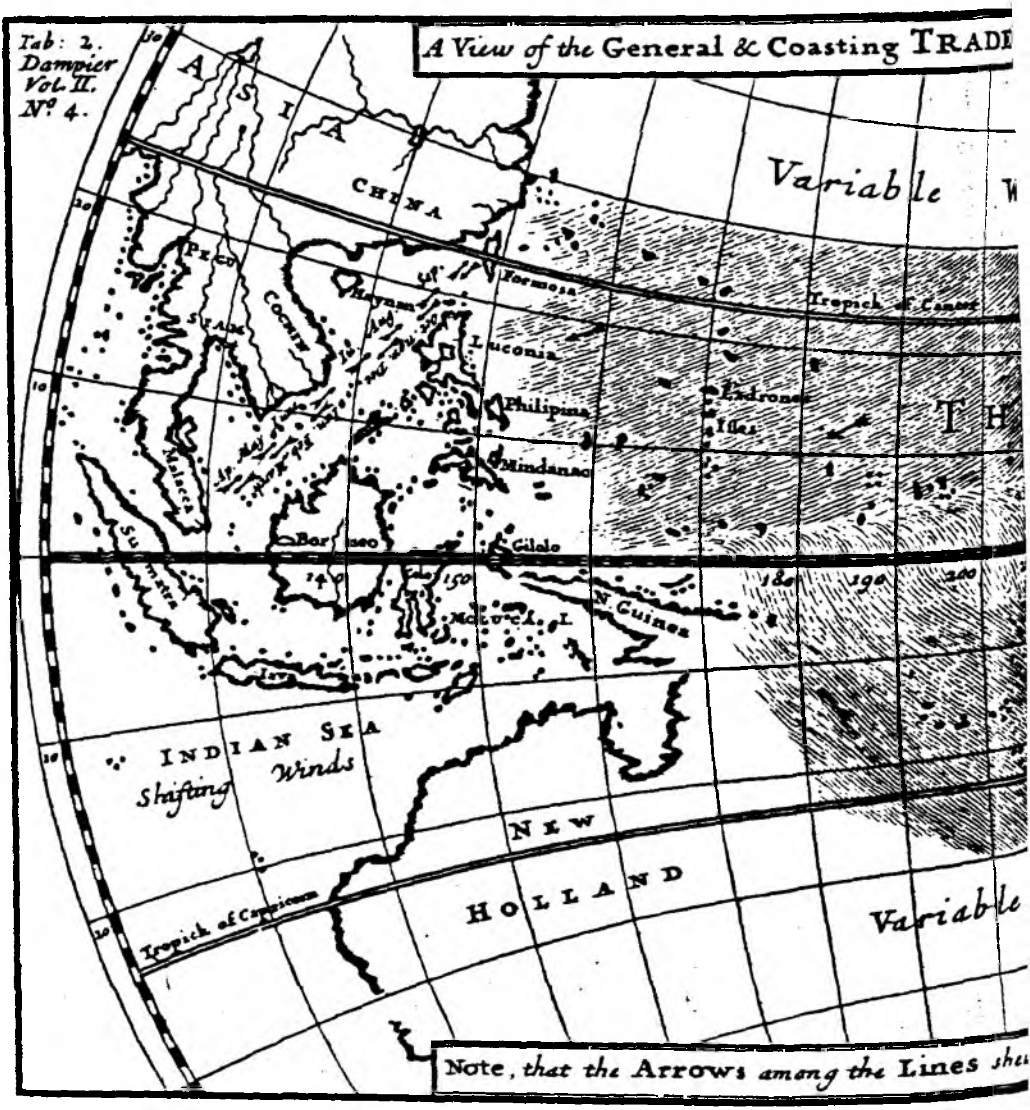
Bermudas
Variable Winds
Maders
Canaries
Spain
Barbari
Hispaniola
Caribbees
NORTH SEA
Gualata
Trinidad
VENEZUELA
FIRM LAND
Caribana
A
Guinea
320
340
350
360
10
20
AMAZONES
C. Blanco
BRASIL
THE ETHIOPIAN
S. AMERICA
PARAGUAY
Variable Winds
R. de la Plata
1 Aruba
2 Querimo
3 Barbados
4 Isles of C. Verd
Note, that the Arrows in the void Spaces shew the Cours
Shew the Times of the Year when such Winds blow.

FIG.5a. Charts of prevailing surface winds for the tropical Atlantic and Indian oceans contained in *Discourse of the Trade-Winds, Breezes, Storms, Seasons of the Year, Tides and Currents of the Torrid Zone throughout the World* (DAMPIER, 1699); reproduced from BELL (1931).


Tab: 2.
Dampier
Vol. II.
No. 4.
A View of the General & Coasting TRAD
ASIA
CHINA
PEGU
SIAM
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Haynan
Formosa
Luconia
Philipina
Mindanao
Malacca
Sumatra
Borneo
Gilolo
Moluccas I.
N. Guinea
Java
Ladrones Isles
Variable W
Tropick of Cancer
TH
INDIAN SEA
Shifting Winds
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Note, that the Arrows among the Lines she

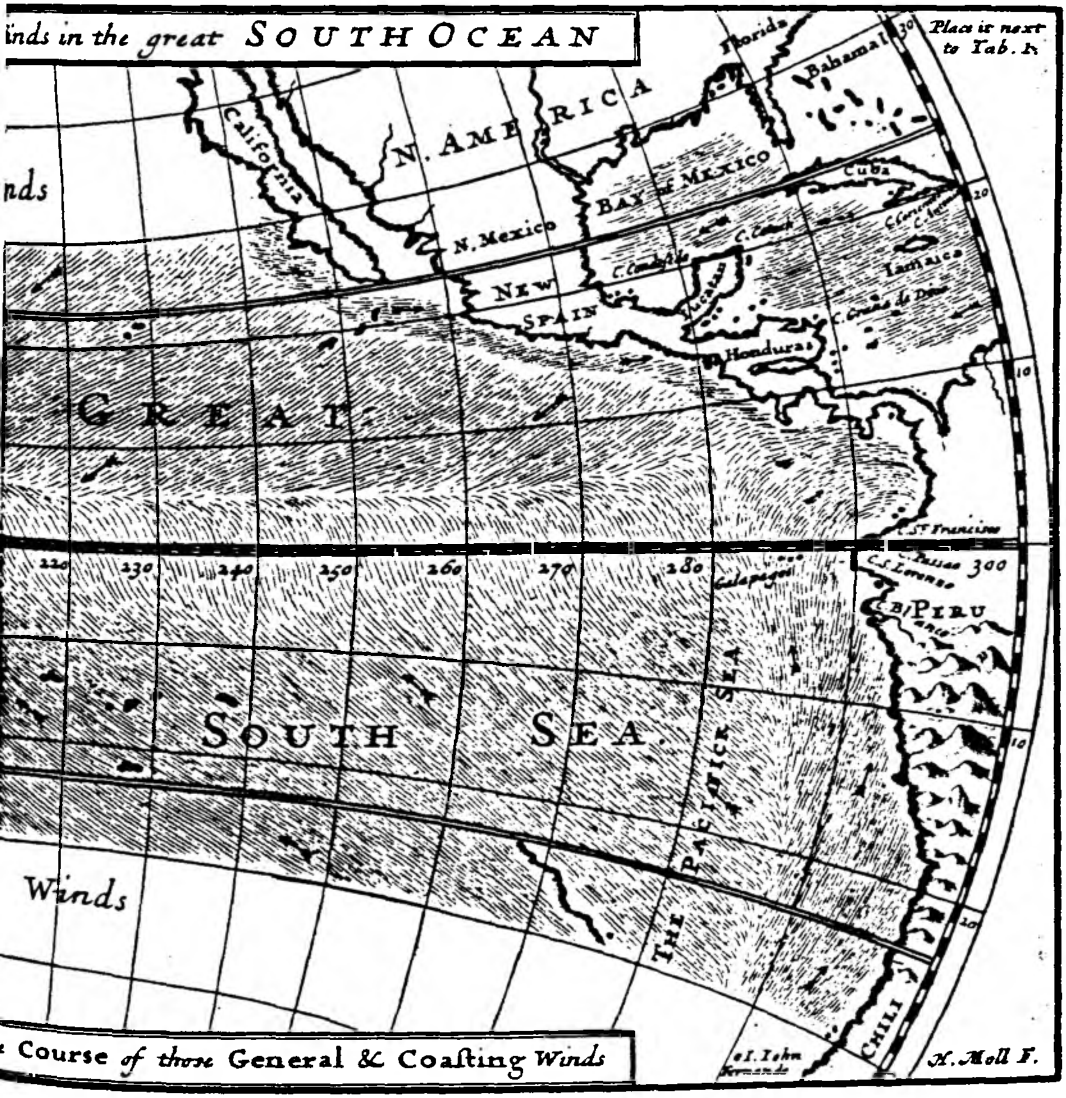


FIG.5b. Charts of prevailing surface winds for the tropical Pacific contained in *Discourse of the Trade-Winds, Breezes, Storms, Seasons of the Year, Tides and Currents of the Torrid Zone throughout the World* (DAMPIER, 1699); reproduced from BELL (1931).

buccaneers was harbored. Dampier yielded to temptation and joined the pirates, a move that would ultimately establish him as the leading British navigator and travel-writer of his time. His adventures took him to the coast of Africa, and west around Cape Horn to the western coast of South America. When the buccaneering party broke up, Dampier and others crossed the Pacific to the Philippines, where he endured many hardships but was able to preserve his journal. He finally returned to England after a twelve-year absence, in 1691.

Dampier published his adventurous accounts for popular reading in his *Discourse*, which won great success, but it was actually meant more for the practical use of seamen. In it, DAMPIER (1699) described the trade winds much like HALLEY (1687) had, and included two charts of them (Fig.5): one for the Atlantic-Indian oceans similar to the world's first chart of winds by Halley, and another for the Pacific Ocean that has no counterpart in Halley's work. Dampier's charts are pertinent because "Tis generally observed by Seamen, that in all Places where Trade-winds blow, the Current is influenced by them; but 'tis not with a like swiftness in all places; neither is it always so discernable by us in the wide Ocean....yet even there the Force of the Winds constantly blowing one way, may, and probably does, move the Surface of the Water along with it". Dampier thus reiterated the concept of wind forcing the surface circulation, and went further than Varen in clearly attributing the equatorial currents to wind, something that Vos, Kircher and other writers of the period would not do. As opposed to those writers, there seems to have been little doubt now in the minds of seamen about the wind's primal role in forcing the circulation of the ocean, though the mathematical formulations for proving it on a rotating Earth were still two centuries away.

Dampier made a clear distinction between tides, which he described as running forward and back again twice a day and most strongly felt near coastlines, and currents, which are much more constant and can be felt at remote distances from land. He repeated the importance of wind in creating ocean currents by saying, "From thence it may be inferred, that the Southerly Winds on the Coast of Africa, and the true Trade between it and Brazil, gently move the surface of the Sea to the Northward, slanting in on the Coast of Brazil; which being there stopped by Land, bends its Course Northerly towards Cape St. Augustine (near present-day Recife): And after it has doubled that great Promontory, it falls away more gently towards the Coast of Surinam; and from thence towards the West-Indies". The experience of tropical currents near land (where they could be measured) being in the same general direction as the winds led Dampier to the supposition that the same is true away from land. He then described what we now call the monsoon currents in the Indian Ocean, the Benguela Current, North Brazil Current, the Gulf Stream, the Peru Current, the southern end of the California Current, and the equatorial currents in all three oceans. The convention of assigning names to currents had still not arrived as he identified them only by location and direction of flow, as Varen and others had done. Though lacking detail, Dampier's descriptions of all these currents were essentially correct, and he attributed them to wind. His charts of surface winds in the tropics might thus be regarded as representing his ideas of how the patterns of ocean currents should look. (A feature to note in the Pacific chart is that the Intertropical Convergence Zone is correctly shown north of the equator.) Although restricted to the tropics, these maps represent a large improvement in objectivity over those given by KIRCHERI (1664/5) and HAPPEL (1685).

2.5. *Eighteenth Century – regional currents; water properties and convection*

Aside from what was being said by writers who adhered to the Aristotelian view of the universe, the seventeenth century witnessed slow, but steady gains in acquiring empirical knowledge of the ocean's movements. The gains of practical knowledge and exchanges of information among seamen accelerated into the eighteenth century, though little noticed by the literary world. Academic interest in Earth's fluids continued to be focused on ocean tides, and more so, on problems of the atmosphere, in particular the question of what produces the trade winds and why they do not blow in a strictly zonal direction. The idea of the Sun heating the air in low latitudes, thus causing it to become less dense, had been around for some time, as had Galileo's notion that air in the tropics does not keep up with Earth's eastward rotation. The accepted cause was not uncovered until George HADLEY (1735) proposed that tropical heating produces a rising motion which sustains equatorward flow at the surface, and that the air particles being drawn toward the equator would be increasingly deflected toward the west owing to the eastward motion of Earth's surface and lengthening circles of latitude. The northeast trades north of the equator and southeast trades south of it were thus for the first time satisfactorily explained on the basis of the combined effects of meridional pressure gradients and Earth's rotation. He argued also that a compensating downward motion at higher latitudes, of air having high relative eastward velocities acquired at low latitudes, would directly account for the mid-latitude westerlies at the surface, which is no longer accepted.

Five years later, Colin Maclaurin brought up the possible influence of Earth's rotation on ocean currents, though in much less specific terms. Maclaurin, a protégé of Newton, responded in 1740 to the offer of a prize by the French Academy of Sciences for a theory that could be used to predict tides. Maclaurin's *De causa physica fluxus et refluxus maris* shared the prize with three other papers. In it he mentioned that the motion of water can be disturbed by Earth's diurnal rotation, but he elaborated only by saying (for the northern hemisphere) that if water moves from the south toward the north, as a result in some way of heat, it would be gradually deflected toward the east, and conversely, if the initial motion were from north to south the deflection would be toward the west (see BURSTYN, 1966a; DEACON, 1971). He did not discuss vertical motions caused by heating or cooling, nor did he make reference to any specific currents. Because his remarks, published in Latin, were very brief and general, and because they appeared where those persons most concerned with ocean currents would likely not see them (we have seen no citations to Maclaurin in any of our source materials), they seem to have made no impact and were lost from view until more modern historical investigations. As before, the main advances with regard to ocean circulation continued to be with the assemblage of direct observations of surface currents.

2.5.1. Walter Hoxton. In the two centuries following the Spanish discovery of the Gulf Stream, very little work had been done to examine it in any detail, which is remarkable in view of the strong trade links established long before between Europe and North America. A British sea captain, however, by the name of Walter Hoxton, kept records of his ship's north-south set as determined from differences between latitude sightings and dead reckoning positions over the course of twenty-three voyages between England to Maryland. In the year 1735 Hoxton drew a large-scale mariner's chart of Chesapeake Bay, and he included on it a legend describing the mean positions and strengths of the "Northeast Current" and counter currents to either side. The positions tabulated and commented upon by Hoxton have since been plotted on a chart from that era by RICHARDSON (1982), and his rendition is reproduced in Fig.6. As Richardson pointed out, Hoxton's location for the Gulf Stream, and his estimate of 1.3 knots for its mean speed agree well with modern estimates, though Hoxton's width for the current is smaller than what we now know it to be. Hoxton was also unable to resolve the very narrow core of the current where speeds of 4 or 5 knots can occur. Hoxton's observations have been fully described by RICHARDSON (1982).

2.5.2. William de Brahm; Benjamin Franklin. The term "Gulf Stream" came into general use shortly after the time of Hoxton, probably around 1760. In September 1748, a Swedish naturalist, Pehr Kalm, was sailing from England to Delaware when he wrote of the ocean seemingly being

FIG.6. A reconstruction of the course of the Gulf Stream according to Hoxton in 1735 (from RICHARDSON, 1982).

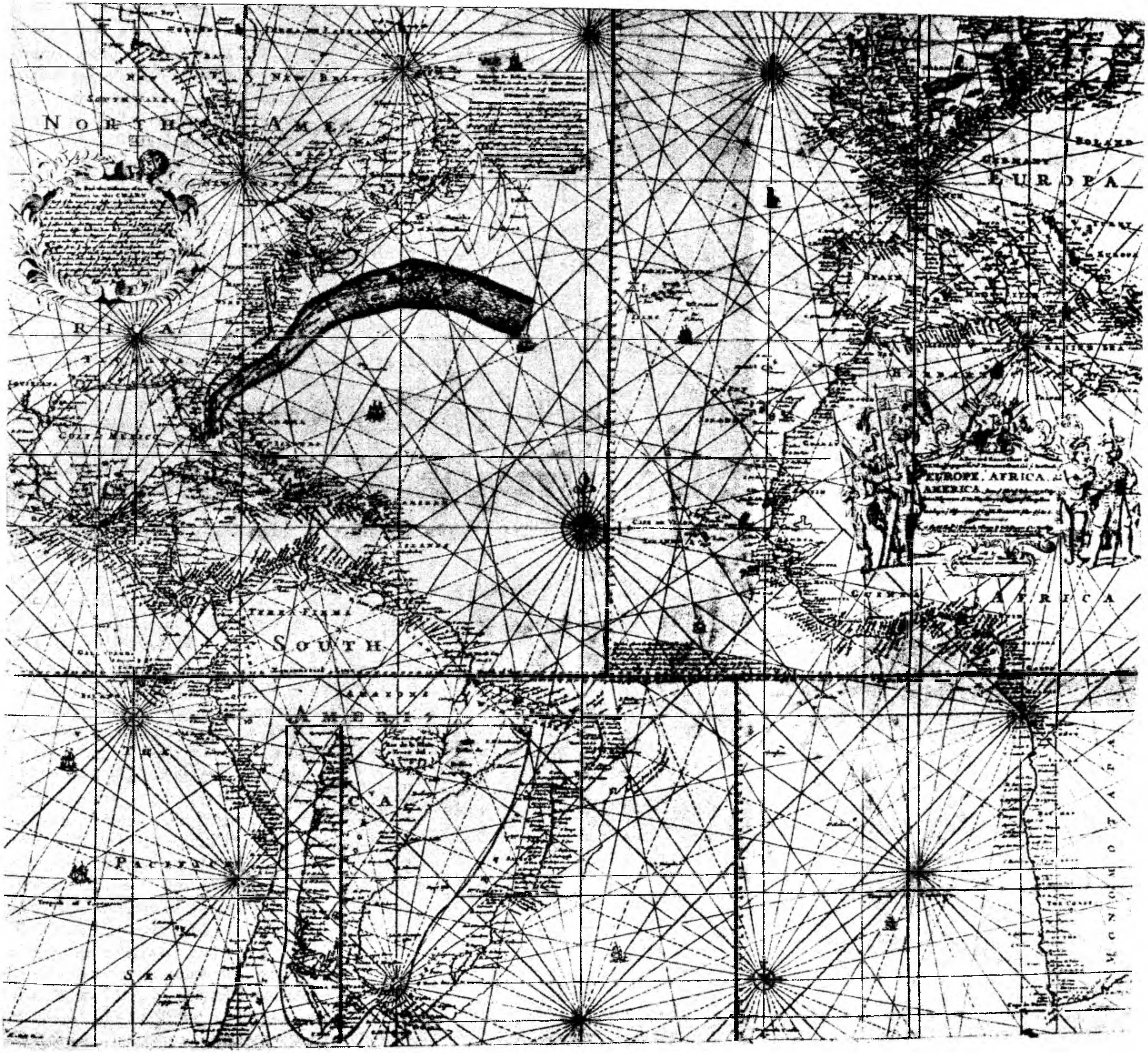


FIG.7. The first Franklin-Folger chart of the Gulf Stream, printed in 1769-1770.

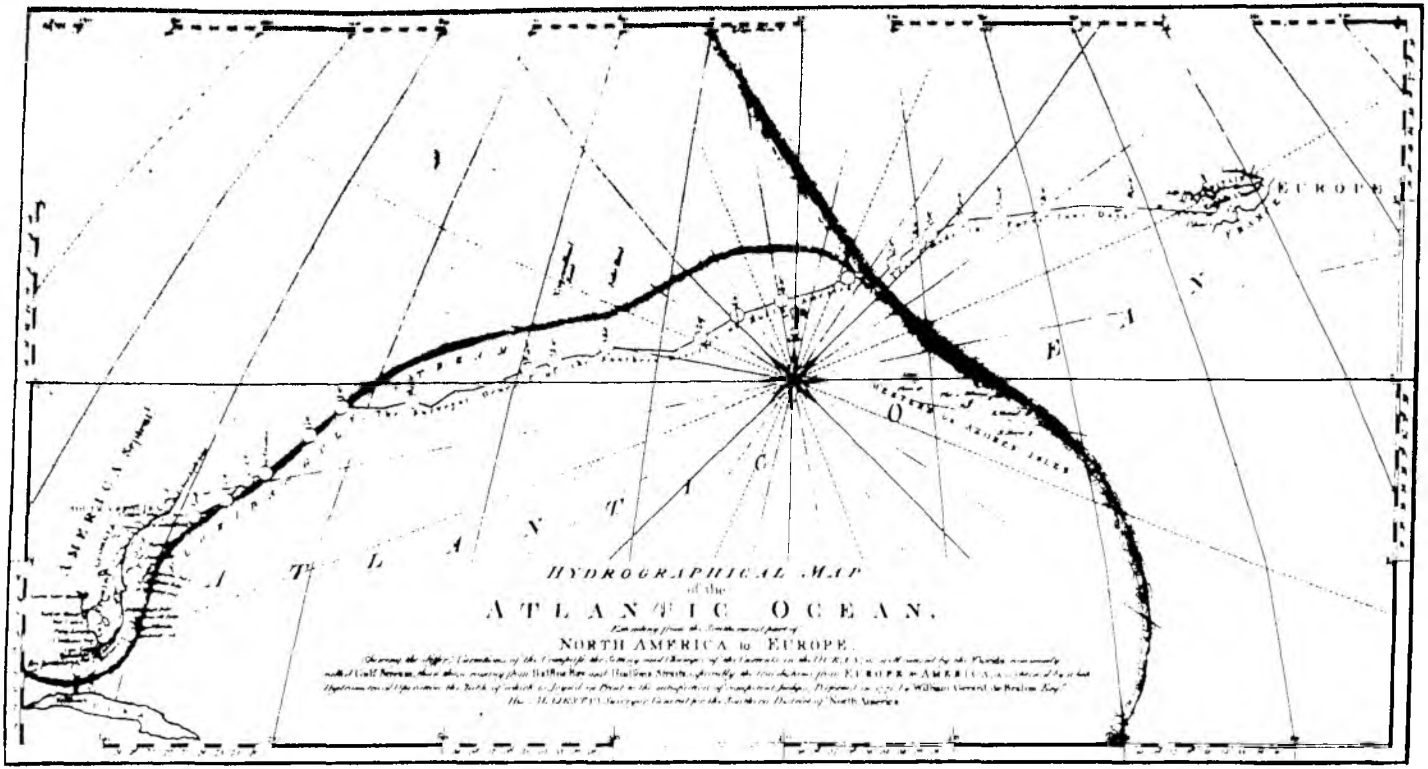


FIG.8. Chart of the Gulf Stream as drawn by de Brahm in 1771 and published in 1772 (from DE VORSEY, 1980).

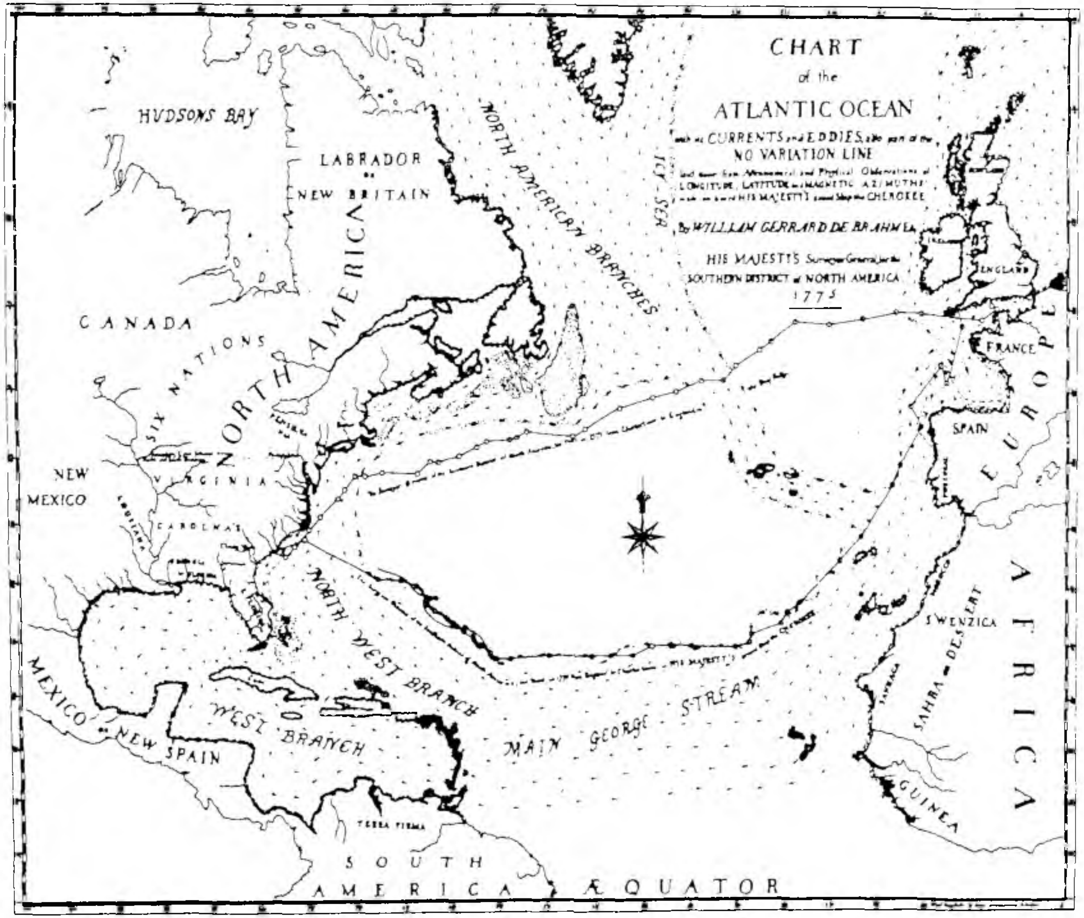


FIG.9. Chart of surface currents in the North Atlantic by DE BRAHM (1775), reproduced fromDE VORSEY (1980).

Like others before, Franklin attributed the strength of the Gulf Stream to the action of the trade winds in the tropics, which was by then a widely accepted idea according to DE BRAHM (1772). Franklin believed that the wind-driven accumulation of water on the northeastern coast of South America ran downhill in a strong current into the Gulf of Mexico and from there toward the Newfoundland Banks. The downhill-running aspect, as we have seen, was discussed as early as 1575 by Thevet, while nineteenth-century writers such as Herschel later argued that the change in level was necessary. This remained the most widely accepted theory for the strength of the Gulf Stream to as late as the mid-twentieth century (SVERDRUP, JOHNSON and FLEMING, 1942), until STOMMEL (1948) identified the cause for the western intensification of basin-scale gyres to be the latitudinal variation in the strength of the apparent deflecting force of Earth's rotation.

Because the Franklin-Folger chart of 1769/70 went rapidly into obscurity, and because the second version, c.1778, was printed in France and not widely distributed, the map did not become well known until the third version was published in 1786. This follows by fourteen years a short book by de Brahm, *The Atlantic Pilot*, published in London in 1772, which contains a chart showing the Gulf Stream as part of the overall circulation in the North Atlantic (Fig.8). De Brahm believed that water pushed into the Gulf of Mexico by the trade winds was compressed by land to form a powerful current at the outlet between Florida and neighboring islands before flowing north and northeast toward the Newfoundland Banks. He described his flow as joining with waters coming from the north and then setting off southeastward across the Atlantic toward the Azores (perhaps a chance description of the origin of the Azores Current), and then south along the African coast until it turns west with the trade winds. This is just the second explicit description we have found of the gyral pattern of flow in the North Atlantic, the first given more than a century earlier by VOSSIUS (1663).

In a longer unpublished and obscure manuscript, *Continuation of the Atlantic Pilot*, DE BRAHM (1775) expanded his descriptions and included another chart, recently redrawn by DE VORSEY (1980) and reproduced as Fig.9. This is the earliest chart we know of that shows the complete gyral pattern of flow in the North Atlantic. Because of his loyalty to King George III, de Brahm called this closed system the "George Stream," and discussed how it splits into two branches, one entering the Gulf of Mexico and the other flowing toward the northwest. The branch entering the Gulf of Mexico through the Yucatan Strait can be seen to form an anticyclonic cell filling the Gulf. With regard to the southward flow along the north African coast, he supposed that it would move into the southern hemisphere were it not for the trade winds and a "contra acting power of an undoubted similar Stream in the Southern Hemisphere". He was assuming the existence of a northward surface current in the low latitudes of the eastern South Atlantic.

A major discrepancy between de Brahm's descriptions and what present measurements show is that he had the Gulf Stream continuing along the ocean's western boundary to Nova Scotia before turning seaward over the southern edge of the Newfoundland Banks. RICHARDSON (1982) has drawn a composite chart of the positions of the Gulf Stream according to Hoxton, Franklin and Folger, and de Brahm (Fig.10), and according to Richardson the anomalous far north position of the current shown by de Brahm may have misled navigators into altering their course into the Gulf Stream when they might have actually wanted to avoid it. The interested reader is referred to DE VORSEY (1980) for more of what de Brahm had to say, and to KOHL (1868) and STOMMEL (1965) for detailed historical reviews of the Gulf Stream.

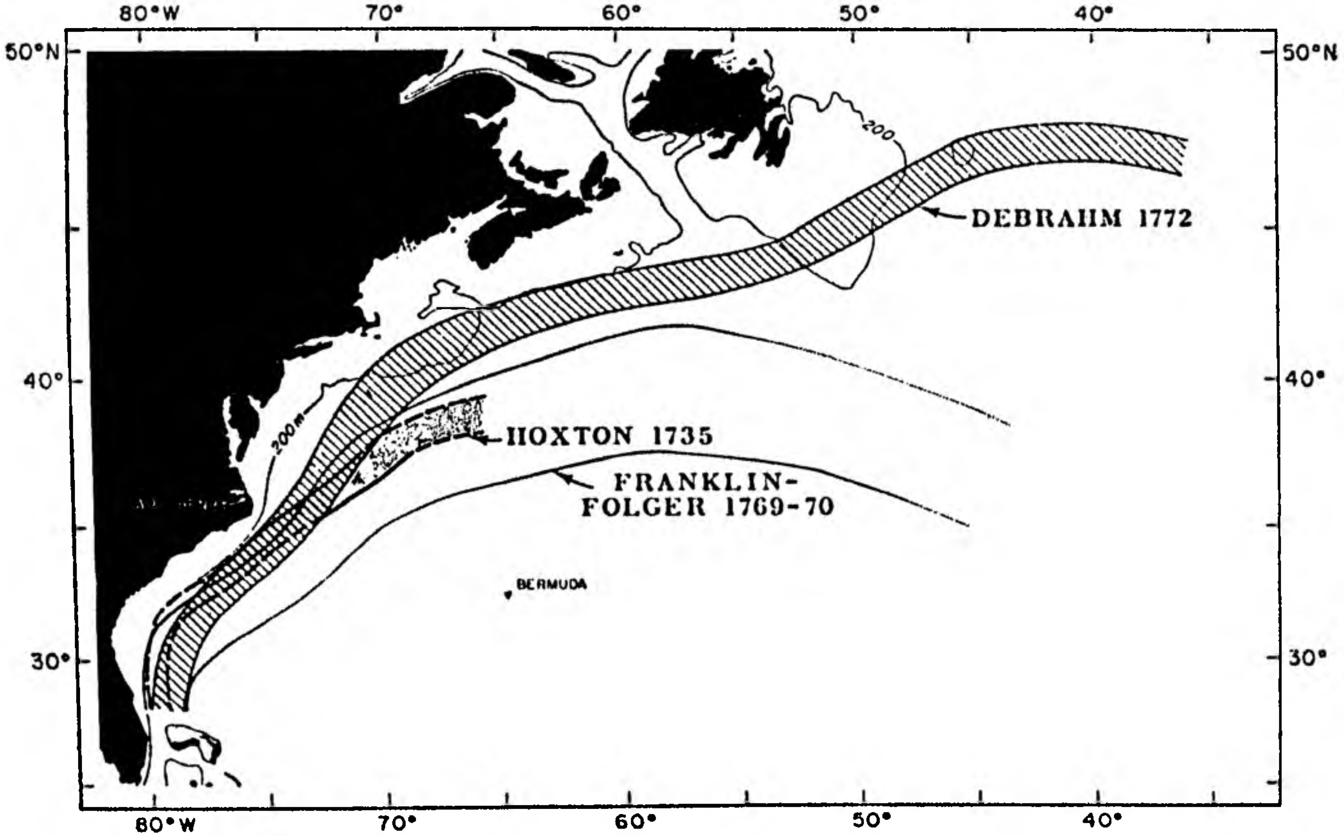


FIG.10. Positions of the Gulf Stream as reconstructed from the indicated sources (from RICHARDSON, 1982).

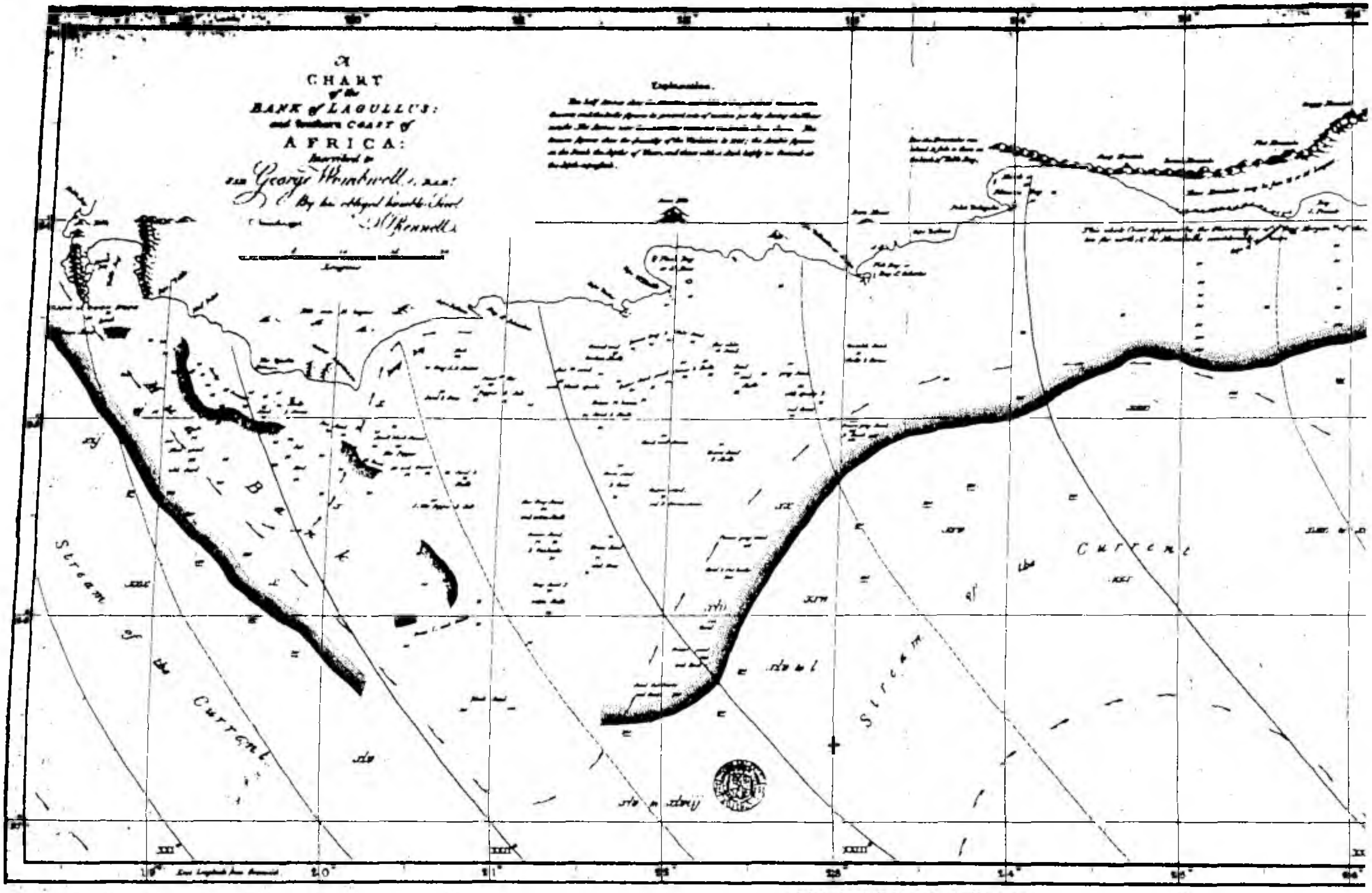


FIG.11. RENNELL's (1778) chart of currents off the southern terminus of Africa (from DEACON, 1971).

2.5.3. James Rennell. As with the Gulf Stream, the Agulhas Current is situated along important trade routes, so it also became the focus of increasing attention during this period. The first methodical study of the Agulhas, based on estimates of ships' drift garnered from a large number of log books, was carried out by James Rennell (1742-1830), who served in the British Royal Navy from 1756 to 1763 and became an expert marine surveyor. He then joined the East India Company in 1764 as its surveyor general in Bengal, and upon taking his assignment a certain Captain Waghorn informed Rennell of the need for a close inspection of the Agulhas Current (FINDLAY, 1866, 1877). This communication ultimately proved to have great consequences for the history of oceanography, because Rennell undertook the task and for the rest of his life he maintained a strong interest in ocean circulation. As we detail in Sections 3.2-3.4, his later work, done during personal time, set the stage for the early nineteenth century mapping of the global surface circulation.

Rennell explained his observations of the Agulhas Current to the Royal Society in 1777 (FINDLAY, 1883) and in the following year he published the first chart of the region's surface currents (RENNELL, 1778) (Fig.11). He found the current to follow the edge of the Agulhas Bank and not the coastline as previously had been believed; submerged features were now seen as having important influence on surface flow. He also portrayed the Agulhas Current as completely rounding southern Africa to flow unhindered into the South Atlantic Ocean. This viewpoint gained widespread acceptance, and would not be recast for another fifty years until a sharp southward turn-around of the current into the Indian Ocean became clear. Still today, the question of how much of the Agulhas Current escapes the retroflection and leaks into the Atlantic remains an important issue (see PETERSON and STRAMMA, 1991).

Later, RENNELL (1793) described to the Royal Society a current in the North Atlantic flowing toward the east into the southern Bay of Biscay, northward along the French coast and then back out toward the west, which he thought was an endangerment to ships approaching the English Channel. Because of the high esteem Rennell would gain in the coming years, this current, called by others the Rennell Current, remained on charts through at least the first half of the nineteenth century, until the use of chronometric observations failed to confirm its existence. Often this has been considered to be a mistake on Rennell's part, but recent observations by PINGREE and LE CANN (1990) support Rennell, showing that this current varies seasonally and reaches speeds of up to 60cm.s^{-1} (see GOULD, 1993).

2.5.4. Jacob S. von Waitz. As we have seen, Count Marsigli's remarkable study in 1681 of the effects of salt-induced density differences on the flow through the Bosporus Strait were all but ignored by contemporary scientists. In 1735 George Hadley revealed the importance of density changes from surface heating and the ensuing vertical convection in setting up the trade winds, and although this explanation quickly became popular, similar arguments were not applied to the ocean. The sea captain Henry Ellis reported in 1751 to the Royal Society in London about water samples he obtained two years earlier from depths of nearly 1600 m in the subtropical North Atlantic that were almost 20°C colder than the water at the surface (see PRESTWICH, 1876; DEACON, 1971; WARREN, 1981), and again the implications for a deep circulation went unnoticed.

From 1737 to 1751, the German aristocrat Jacob S. von Waitz (1698-1776) worked as an administrator of saltworks and other mines. Earlier education gave him a familiarity with physics and mathematics, and he enjoyed applying scientific knowledge to practical problems. He conducted studies on the properties of salt solutions and how they behave during evaporation and freezing. He also knew of Marsigli's work and extended the theory as an explanation for the currents in the Strait of Gibraltar and furthermore to circulation in the deep oceans. This was presented to the Royal Swedish Academy of Sciences in 1754 and published the following year (WAITZ, 1755). DEACON (1985) has translated passages of the paper and has provided commentary and bibliographic information.

A satisfactory explanation for the strong surface flow of Atlantic water into the Mediterranean had yet to appear, and the underlying outflow continued to escape observation. Variants of the theory of subterranean channels and caverns were still being proposed to account for the apparent surplus of water, but they were becoming increasingly less acceptable; intense evaporation was most commonly invoked. Waitz was skeptical of this argument, so to address the problem he used the best available estimates for evaporation and precipitation, and river runoff while allowing for errors, and showed the impossibility for the sources being balanced by evaporative losses alone. Moreover, he demonstrated that such evaporation would have long since caused the Mediterranean to become briny if not solid salt. He saw only one logical explanation, that there had to be a subsurface return of water into the Atlantic: "The lighter water from the Atlantic runs in, becomes saltier and heavier through evaporation, sinks to the bottom there, by reason of its increased weight, pushes aside the lighter water already standing outside and so finds a natural outlet" (from DEACON, 1985). The only difficulty Waitz had with this explanation was that it seemed to conflict with current concepts of hydrostatics, but he thought other arguments had much more severe limitations than this.

Waitz extended his view of the effects of density differences to the deep circulation in the global ocean. His theory continued to focus on density variations resulting from salinity in the absence of similar effects from temperature. He noted how salt is discharged from sea-water upon freezing and that the surface waters of the polar regions are then freshened by summer melting. He argued that because surface salinities are higher in the low latitudes, a similar sort of vertical circulation should occur in the open ocean as between the Atlantic and Mediterranean. He thought polar water should flow toward the equator, get saltier, sink, and return toward the poles at depth. Today we observe only portions of such a system in operation, most notably the equatorward spreading of relatively fresh and cold Antarctic surface waters that are replaced by poleward motions at mid depth of warmer, more saline waters; this layering would be statically unstable without the salinity structure. The actual situation as we see it now is much more complex than Waitz could have imagined because of the additional effects of temperature variations on density, the action of winds upon the sea surface, and the effects of Earth's rotation. The ways in which the densities of salt and fresh water respond to temperature changes had not been adequately realized, and as we discuss in the following, the fundamental mechanics of how heat is redistributed in a fluid were not appreciated.

Waitz published just two scientific papers, the other being on the causes of electricity. Even more so than Marsigli, Waitz suffered from not being visible to the scientific community. Acting to compound this adverse situation, he published his Gibraltar paper in a relatively obscure journal. The result is that his explanation for the Gibraltar problem was not noticed by scientific contemporaries (DEACON, 1985) and the effects of density on ocean circulation would continue to be recondite.

2.5.5. Benjamin Thompson (Count Rumford). In a prelude to presenting results of his research, RUMFORD (1797) wrote *Danger of admitting received Opinions in Philosophical Investigations without Examination.* "It is certain that there is nothing more dangerous in philosophical investigations, than to take anything for granted, however unquestionable it may appear, till it has been proved by direct and decisive experiment. I have very often, in the course of my philosophical researches, had occasion to lament the consequences of my inattention to this most necessary precaution". Sir Benjamin Thompson, Count of Rumford (1753-1814), was referring in this case to a widely-held assumption that fluids are efficient conductors of heat. He showed this to be inaccurate, and that water in particular is an exceptionally poor conductor of heat. He also showed that dissolved salts significantly alter the behavior of water density as a function of temperature, and that this in combination with water's poor heat conduction leads to great consequences for ocean circulation and global climate. Although Rumford was read by a wide audience, he is now cited only briefly in the oceanographic literature, and this compels us to take a closer look at him and his work.

Thompson's extraordinary personal history is laid out in the engaging biography by BROWN (1979). Thompson was born into a prosperous farming family in Woburn, Massachusetts, but he displayed an early disaptitude for farming. This led his father to indenture him to a merchant in nearby Salem, where he received his formal education. He took particular interest in scientific and medical subjects, and in 1772 he accepted a position as schoolmaster in Concord, New Hampshire (then a part of the town of Bow, a part that had until about a dozen years earlier gone by the unofficial name of Rumford, Massachusetts). Thompson, who had an aggressive personality and a gift for political and interpersonal manoeuverings, soon became discontented with his work and social status. Shortly after arriving in Concord he married a wealthy widow twelve years his senior and started off on a series of adventures. He spied on revolutionary colonists for the British, served in the Royal Navy, and commanded British soldiers in America during the war. Following the war Thompson abandoned his wife and young daughter for London and was conferred a knight by King George III. Sir Benjamin was sent to Bavaria to serve as a British intelligence agent in the court of the monarch Char Theodor. After his arrival in Bavaria, Thompson spent a summer at the Theodorian Academy of Sciences in Mannheim, established by his devout host for the purpose of revealing divine beauty in the workings of nature. There he conducted some of his early experiments on heat. His usefulness to the British declined, and within a year he was completely in the service of Bavaria and Theodor. Thompson's primary duties to Theodor concerned the military, which was racked by inefficiency and corruption. The reforms Thompson instituted, and his other efforts to ingratiate Theodor (who was also an elector to the Holy Roman Empire), were highly successful. In 1792, at the age of just thirty-nine, Thompson was elevated to the noble rank of count. For reasons that remain unclear, he chose the name Rumford over others that would have been more appropriate according to traditional practice.

Count Rumford had become wealthy and his noble rank allowed him to take distance from a disagreeable political atmosphere in Munich, so he was in the position of having the time and resources to pursue his interests in science. These centered on optics and the transfer of heat, and later on improvements in the designs of cooking utensils and fireplaces for which he gained fame among the populace. The term "Rumford stove" is with us today. While still believing that heat should pass unhindered through materials, he made an observation that to his surprise had not been made before. Recalling a visit to Naples in 1794, Count RUMFORD (1797) wrote: "I was much struck with several very interesting phænomena which the hot baths of Baiæ presented to my observations, and among them there was one which quite astonished me: standing on the sea-shore near the baths, where hot steam was issuing out of every crevice of rocks, and even rising up out of the ground, I had the curiosity to put my hand into the water. As the waves which came from the sea followed each other without intermission, and broke over the even surface of the beach, I was not surprised to find the water cold; but I was more than surprised, when, on running the ends of my fingers through the cold water into the sand, I found the heat so intolerable that I was obliged instantly to remove my hand. The sand was perfectly wet, and yet the temperature was so very different at the small distance of two or three inches! I could not reconcile this with the supposed great conducting power of water. I even found that the top of the sand was, to all appearance, quite as cold as the water which flowed over it, and this increased my astonishment still more. I then, for the first time, began to doubt of the conducting power of water, and resolved to set about to making experiments to ascertain the fact".

"...In the course of a set of experiments on the communication of Heat, in which I had occasion to use thermometers of an uncommon size (their globular bulbs being above four inches in diameter) filled with various kinds of liquids, having exposed one of them, which was filled with spirits of wine, in as great a heat as it was capable of supporting, I placed it in a window, where the sun happened to be shining, to cool; when, casting my eye on its tube, which was quite naked (the divisions of its scale being marked in the glass with a diamond), I observed an appearance which surprised me, and at the same time interested me very much indeed. I saw the whole mass of the liquid in the tube in a most rapid motion, running swiftly in two opposite directions, up and down at the same time. The bulb of the thermometer, which is of copper, had been made two years before I found leisure to begin my experiments, and having been left unfilled, without being closed with a stopple, some fine particles of dust found their way into it, and these particles, which were intimately mixed with the spirits of wine, on their being illuminated by the sun's beams, became perfectly visible (as dust in the air of a darkened room is illuminated and rendered visible by the sunbeams which come in through a hole in the window-shutter), and by the motion discovered the violent motions by which the spirits of wine in the tube of the thermometer was agitated. ... On examining the motion of the spirits of wine with a lens, I found that the ascending current occupied the *axis of the tube*, and that it descended by the *sides of the tube*".

Rumford surmised that the motions of the liquid particles were a result of them carrying heat and that the heat would remain with the individual particles until given off directly to the sides of the cold tube. He concluded, in contrast to what had been widely assumed, that liquids conduct no heat at all. They of course do conduct some heat, but Rumford was much closer to the truth than the prevailing opinions had been. To support his conclusion further, he devised other experiments to show the importance of vertical convection in transferring heat. One was an ingenious refinement of the above experiment in which he placed bits of amber in a flask filled with water. Amber has a density slightly greater than that of water, so to make the amber neutrally buoyant he added the proper amount of alkali. After placing the flask in a vat of hot water and keeping it there, he once again observed opposing vertical motions, this time downward along the axis and up along the sides. He further confirmed his suspicions of liquids not conducting heat by fixing cakes of ice to the bottom of a vessel and then filling it with boiling hot water; the ice melted at a rate he determined to be eighty times slower than if the ice had been allowed to float on the water's surface.

Another critical finding revealed to RUMFORD (1797) through his experiments concerns the temperature of maximum density of water: "Though it is one of the most general laws of nature with which we are acquainted, that all bodies, solids as well as fluids, are condensed by cold, yet in regard to water there appears to be a very remarkable exception to this law. Water, like all other known bodies, is indeed condensed by cold at every degree of temperature which is considerably higher than that of freezing, but its condensation, on parting with Heat, does not go on till it is changed to ice; but when, in cooling, its temperature has reached to the 40th degree of Fahrenheit's scale, or eight degrees above freezing, it ceases to be farther condensed; and on being cooled still farther, *it actually expands*, and continues to expand as it goes on to lose more of its Heat, till at least it freezes".

The temperature at which pure water reaches its maximum density is actually 39.2°F (3.98°C), so he came close. Furthermore, Rumford found that salt water behaves in a very different manner, that it continues to become more dense as it cools to its freezing point. He immediately realized the immense global consequences of these properties of fresh and salt water: that the surface of freshwater lakes will freeze rapidly during early winter, thus preserving their interiors in the liquid state and maintaining habitat for the life there, whereas the formation of ice on the ocean would proceed in a very much more restricted manner. He recognized that the oceans in high latitudes must necessarily undergo deep convective overturning, far in excess of that which would occur if the oceans were instead composed of freshwater, and because of their great depths and their currents bringing warm water poleward, the oceans release tremendous amounts of heat to the atmosphere, thereby acting as a great modifier to high-latitude marine climates.

RUMFORD (1797) reasoned that meridional circulation cells are set up in the vertical within the ocean: "But if the water of the ocean, which, on being deprived of a great part of its Heat by cold winds, descends to the bottom of the sea, cannot be warmed *where it descends*, as its specific gravity is greater than that of water at the same depth in warmer latitudes, it will immediately begin to spread on the bottom of the sea, and to flow towards the equator, and this must necessarily produce a current at the surface in the opposite direction; and there are the most indubitable proofs of the existence of both these currents". He cited the warm poleward-flowing Gulf Stream as an example of the surface current, and the cold temperatures measured at depth in the subtropical North Atlantic by Captain Henry Ellis as evidence for the deeper flow.

Rumford knew that the density of sea-water depends on salinity as well as temperature, but he discussed density-driven ocean currents only in terms of temperature variations. The reason seems to be that he considered oceanic salinities too uniform to produce their own class of density-driven flow. He wrote of the common knowledge that salts are nearly always uniformly distributed in salt-water solutions, and he performed an experiment to show that this is caused by the motions of water particles in response to variations in temperature. Although he offered no explicit inferences about ocean circulation from this experiment, he may have thought that oceanic temperature variations would act to maintain a near homogeneity of salinity. He appears to have been unaware of the paper by WAITZ (1755) explaining the currents in the Strait of Gibraltar as being caused by salinity-induced density differences, and he also seems to have not known about the earlier but similar work by MARSIGLI (1681). Waitz and Rumford proposed meridional density-driven cells that circulate in opposite ways, and each of their explanations are logical within the limitations of their individual mechanisms; we now see elements of each type of circulation at work in the ocean. Unfortunately, Rumford's measurements and ideas were so at odds with the received opinions that they would be accepted only with reluctance some years later.

3. THE ERA OF CHRONOMETIC OBSERVATIONS

3.1. Invention of the Marine Chronometer

3.1.1. The need. Quadrants had been in use since the 15th century for determining latitude, and with technical developments their accuracies were steadily improved. For longitude, however, all that could be relied upon until the late 18th century was to make educated guesses, called "dead reckoning", based on wind speed, ship's heading, and known sailing characteristics of the particular vessel. It was far less than adequate for determining the zonal set by currents; the locations of islands and other geographical features were often reported by their discoverers with such errors that they were difficult and sometimes impossible to find by subsequent navigators. This led to the cartographical misplacement of a multitude of islands, while others were drawn that were altogether nonexistent (some of which have appeared on modern maps (see STOMMEL, 1984)). As early as the 16th and 17th centuries the problem of longitude had become so pressing that the governments of France, Holland, Spain, and Venice, as well as individual private donors, offered large sums of money to anyone who could find a workable solution. The rewards were offered in vain.

It was well understood that accurate astronomical observations and predictions could in principle provide correct measures of longitude. To develop such an astronomical technique, the British Parliament in 1675 founded the Royal Observatory in Greenwich, charging the Astronomer Royal with "rectifying the tables of the motions of the heavens and the places of the fixed stars, so as to find out the so-much desired longitude of places for perfecting the art of navigation" (WATERS 1973). Improving that art, much less perfecting it, proved to be an extremely slow and tedious undertaking. This was made abundantly clear when in 1707 two thousand British seamen and soldiers lost their lives after their fleet had run aground at the Isles of Scilly, off the southwestern tip of England. The wreck was attributed to poor navigation (the rather rotund commanding Vice-Admiral Sir Cloudesley Shovell was able to float to shore, but he was murdered on the beach by a local woman for his emerald ring). The ensuing sensation in London and the continuing lack of a workable solution motivated Parliament in 1714 to offer, by Act of 12 Queen Anne, a reward to anyone who could invent a method for finding longitude at sea that was both "practicable and useful". The prize was set at £20,000 sterling if the method proved accurate to within ½° longitude on a voyage to the West Indies, £15,000 if within ⅔°, and £10,000 if within 1°. The Board of Longitude was established to oversee the competition.

Astronomers at the Royal Observatory worked during the following decades on the method of lunar distances. It is based on measuring the angular distance between the Moon and Sun, or some other fixed star, and comparing the time of the observation with that of the same astronomical occurrence at Greenwich as predicted by a set of tables. The instruments needed, including quadrants, were inexpensive, but the method required a team of four persons to make an accurate observation and it further required a four-hour calculation using logarithms to obtain a single fix. Very few navigators possessed the mathematical skills necessary to perform the calculations, and the method was further impaired by it being physically cumbersome and usually impossible to accomplish aboard an unsteady ship; slight errors in measurement would lead to unacceptably large errors in position.

The essence of a more practical solution was maintaining, during long voyages, correct Greenwich time. This would be compared with local time, usually determined by observing when the Sun passed the local meridian. Because the Sun's altitude changes very little for some period before and after local noon, a single observation of its highest altitude could not provide the required accuracy, so measurements were made of when the Sun crossed a given angular elevation well before and after noon (the method of equal altitudes). This was fairly straightforward. The difficult part was keeping correct Greenwich time; to qualify for the maximum prize, a mechanical timekeeper had to be accurate to within two minutes, equating to an error of less than two seconds per day over a ten-week voyage – a daunting challenge at best.

Erratic timekeeping was inherent in all clocks and watches of the period, for two principal reasons. These were changes in temperature (causing a pendulum to shorten or lengthen, or for a balance to change size and the elasticity of its spring to vary) and mechanical friction. The best pendulum clocks had errors of as much as two or three minutes a week, well outside the bounds of even the least rigorous limits set by the Act of Queen Anne. Furthermore, the often severe motions of a ship ruled out the use of pendulum clocks. Larger problems with accuracy existed with spring-operated watches, which would be in error by as much as two minutes a day. New technologies had to be developed to overcome these obstacles, so several inventors took to the construction of nautical clocks, or chronometers. But for more than twenty years after the Act of Queen Anne was passed, not a single device was built that could so much as motivate the Board of Longitude to meet. The prize money would not be dispensed for more than fifty years.

3.1.2. John Harrison. The award offered by the Act of Queen Anne was eventually won by John Harrison (1693-1776). With extraordinary mechanical ingenuity, and through a lifetime of work, Harrison almost single handedly revolutionalized horology and navigation, thus making possible the acquisition of previously unattainable knowledge about ocean circulation. But however indispensable his contribution is to oceanography, he has been discussed in only the sketchiest of terms in the oceanographic literature. It is therefore appropriate that a few paragraphs be devoted to him here. The biography by QUILL (1966), from which we draw in the following, is recommended for greater detail.

John Harrison was the first son of a carpenter and surveyor employed by a wealthy owner of estates in Yorkshire and Lincolnshire. John was born in Yorkshire, and when he was around the age of four his family was moved to a remote village in Lincolnshire where he later learned the trades of his father. Not much is known of his early life, except that he had evidently acquired a high level of skill as a clockmaker before reaching the age of twenty. He built a long-case clock in 1713 that still exists, as well as others dating from 1715 and 1717. Clocks and watches were expensive at the time, and uncommon even in large cities, so it is thought he may have had interests in a commercial venture. According to QUILL (1966), Harrison likely learned of the prize offered by the Act of Queen Anne shortly after he completed his clock of 1717, and that he was probably involved in clock and watch repair during the period of 1717-1726. During this time he was joined in the work by his brother James, who was ten years younger.

Though the brothers were apparently not working with the prize money specifically in mind, it is thought to have provided a measure of stimulation. Together they meticulously carried out extensive experiments aimed at tracing and eliminating the errors in mechanical timekeeping, for which they also had to acquire skills at making astronomical observations. By 1726 they built a pair of long-case clocks introducing several important technical advances. The pendulums (called gridirons) were made of alternating rods of steel and brass, which have different rates of thermal expansion, arranged in such a way that the pendulums were unaffected by changes in temperature. The escapement (which parcels the changing force of the weights into even amounts before being delivered to the pendulum, by allowing a tooth to escape from a pallet at regular intervals) was the first "grasshopper" escapement, an innovation with greatly improved efficiency and a minimum of friction. Moreover, they were the first to use roller bearings in clockmaking. The bearings, as well as the gears, were made of a heavy, naturally oily tropical wood that eliminated the need for lubrication. These clocks, termed precision regulator clocks, were tested to have errors of no more than a second a month, making them by far the most accurate clocks the world had seen.

This great success led the Harrisons to devise ways of adapting their unique mechanisms to a portable clock that could be used at sea. By around 1730 the brothers had conceptualized an entirely new form of timekeeper that would require no pendulum in the ordinary sense. But the clock had to be made with brass parts, which the Harrisons were ill-equipped to make and unable to afford. John travelled to London with drawings of the envisioned machine and obtained an interview with Edmond Halley (1656-1742), the Astronomer Royal who was also a Commissioner of the Board of Longitude. Halley was highly impressed by their conversation, so he referred Harrison to George Graham, also a commissioner and a maker of clocks and scientific instruments. After a conversation that lasted a full day and into the evening, Graham was so impressed that he generously provided a personal loan to Harrison and then arranged for others to be made so that the new clock could be built.

Harrison completed his first sea clock (H1) in 1735. It was a machine measuring nearly a meter on each side and weighing over 30kg. Instead of a pendulum, it had a pair of balances in the shape of single-ended dumb-bells that oscillated from side to side and which were arranged so their movements would be unaffected by the motion of a ship. The Board of Longitude had, as of yet, never met, so to avoid the protracted process of getting its members together, Halley and Graham, who were Fellows of the Royal Society, got three other Fellows to join them in giving H1 a thorough inspection. Though the machine was large, the outcome was resounding support and a certificate was issued by the Royal Society to Harrison honoring his work and the machine. Through the Admiralty, the Society arranged for a preliminary trial of H1 on a naval vessel. The trial took place in 1736 when Harrison and his machine sailed to Lisbon. The machine worked well during the voyage, but the captain of the ship fell ill en route and died in Lisbon, the result being that no navigational information was recorded. Near the end of the return trip, however, Harrison used his machine to correctly determine that the careful dead reckoning carried out by the ship's company was some 57 nautical miles in error. This motivated the Board of Longitude to finally meet, for the first time since their inception twenty three years before. Here Harrison showed the machine, but instead of asking for a sea trial to the West Indies as outlined by the Act of Queen Anne, he offered to make another, smaller machine that would be of an improved design correcting some defects he had found. To allow him to do this, Harrison asked for, and was awarded, £500.

The Harrisons took up residence in London, but their working relationship ended in 1739 when James returned to Lincolnshire. In about a year, the second sea clock (H2) was completed. It had a much improved temperature compensator, still in the form of the older gridirons, as well as a mechanism employing a secondary spring (a remontoire), features that made this machine significantly better than H1. But it was still just as large and heavy, and did not perform to Harrison's exacting standards. So when the Board met in 1741, Harrison again declined to ask for a sea trial. He reported that he was unsatisfied with the large dumb-bell shaped balances, and that he had already begun work on another machine with circular balances. He was awarded support for building H3, the first sea clock he would construct without the aid of his brother.

To use circular balances, Harrison had to devise a new type of temperature compensator. This was in the form of strips of brass and steel fastened together along their lengths that would curl under varying temperatures. These "bi-metallic curbs", which are still used in various applications today, were ingeniously designed to do mechanical work inside the clock. This again was a significant advance, but work on H3 turned out to be greatly frustrating. It was not until 1755, after having been saved from bankruptcy by a Board whose membership was quite different from the original, that Harrison could finally predict that it would be ready for a sea trial the following spring. He also told the Board that he had been working on a pair of watches, one the size of a pocket watch, the other much larger. He produced drawings of these, and once again obtained monetary support. In fact, H3 was never tested at sea and in 1760 Harrison abandoned developmental work on it altogether in favor of his large watch. The problem, unknown to him during the nineteen hard and often desperate years he spent working on H3, was a lack of isochronism arising from a single spring actuating both balances, which had no common period of oscillation. The dynamics of this phenomenon were not yet understood.

Harrison's large watch (H4) proved to be the most famous and important watch ever made. He showed his masterpiece to the Board in 1759—it was nearly 12 cm in diameter and made of finely detailed silver; it had little in common mechanically with his previous timekeepers. It required lubrication, though a minimum amount as Harrison had become a pioneer in the use of jewelled bearings, and it had a special verge escapement. Like H3 it had a bi-metallic temperature compensator and a remontoire. Although the watch had just recently been assembled, Harrison took pleasure in reporting to the Board that its accuracy was far greater than he had expected. He requested that both H3 and H4 be tested during a single trial the following year. The reaction was one of marvel. This watch had been in the making for only five years, and for such a small device to hold such great promise was nothing short of fantastic.

Harrison reported in early 1761 that his watch was continuing to perform with great accuracy and that he was ready to test both H3 and H4 on a voyage to the West Indies. The Board assented, but their instructions to Harrison were preliminary, brief and vague, apparently because they had come to doubt that either device could seriously contend for the prize. Because of his age, Harrison requested that his son William make the trip, to which the Board also agreed. But the Board failed to provide further instructions as they had promised, causing William to spend five solitary months at port in futile wait. The experience was exasperating for both John and William, and it was only the beginning of a long pattern of increasingly callous treatment the Harrisons would receive by the Board.

The Board met again in October 1761. Specific plans for a sea trial were agreed upon, but because Harrison had probably concluded that H3 would not provide satisfactory results the plans now involved only H4. The next month William was finally at sea with his father's watch, on a ship steering a course first for Madeira and then Jamaica. The watch was given its first practical test when the ship approached the latitude of Madeira. Dead reckoning indicated the ship was east of the island, in which case a westward turn with the trade winds would have made it easy to reach the island. But Harrison's watch indicated that the ship was actually west of the island, some 100 miles west of what had been estimated by dead reckoning. William predicted that by maintaining the course they were already on they would be in sight of the island the next day, and although the captain was sceptical, he consented to do so. William was proven correct the next morning – even though an unexpected current set the ship west. After leaving Madeira, William continued to calculate the ship's position, keeping his results private until the day before he thought land would be sighted. He predicted the sighting to within three hours, much to the amazement of the ship's company who thought from dead reckoning they were more than 150 miles farther to the east. Thus, nearly a decade before the first Franklin-Folger chart of the Gulf Stream was printed, the effects of zonal surface currents were detected on the basis of accurate timekeeping.

Owing to logistical reasons and weather, William was able to determine the local noon by equal altitudes on only one of the nine days he was ashore in Jamaica. The watch was in error by 2 minutes 36 seconds, but after applying a correction for the known drift, or "rate", of the watch, the Harrisons reported an actual error of just 5 seconds. It was well within the limits set for the highest prize. But for several reasons, among them being that the Harrisons had not revealed the drift rate until after the calculations were made, the Board of Longitude concluded that the rules set down by the Royal Society had not been followed. At the heart of the matter was the wording of the plans that were earlier agreed upon, and the wording of the Act of Queen Anne itself. The Board needed to protect itself against making a rash award, so none was made. The raw error equated to an error in longitude of slightly less than one degree, just within the limits for the ten thousand pound prize, but Harrison felt indignant at being mistreated and would not claim it. To deal with all disputes and settle the issue, the Board proposed that a new test be conducted which would allow for no ambiguities. They also awarded Harrison £2500, to be deducted from any future prize winnings, in recognition of his achievements being of "considerable utility to the public". Harrison agreed to the new test, though he maintained that the watch had been proven.

An influential person with the Board of Longitude, though he was not on it himself, was the Rev. Nevil Maskelyne. He had been working on the method of using lunar distances, as had some of the board members, so Harrison was of the cynical opinion that unfair leverage was being used against him. His suspicions were reinforced by recent progress made with lunar distances that had brought the method close to the accuracy needed to contend for the prize. This was made possible by John

Hadley's (brother of George Hadley) invention in 1731 of a reflecting octant that could be used effectively at sea, and by greatly improved lunar ephemeris tables constructed by Tobias Mayer (1723-1762) during 1751-1753. As several members of the Board were astronomers, who understood the lunar method and not the unknown mechanical principles Harrison kept secret, Harrison's suspicions may have had some justification. But Harrison's outspoken personality merely aggravated the situation, as he took to publicizing his mistrust in the form of broadsheets entitled *The Case of Mr. Harrison* whenever he and the Board disagreed.

Serving to heighten Harrison's mistrust was Maskelyne's appointment by the Board to participate in the second trial, both in connection with testing Harrison's watch and in conducting experiments with the method of lunar distances. Owing to Maskelyne's health, and the presence of infectious diseases in Jamaica, the trial was made to Barbados. Maskelyne departed England in late 1763 and William Harrison with his father's watch in early 1764. Using the lunar method while at sea, Maskelyne predicted the longitude of Barbados to within ½°, a long sought after result that was enormously pleasing to Maskelyne. When William later arrived in Barbados and learned of Maskelyne's open enthusiasm for the method that had been under development since the founding of the Royal Observatory in 1685, animosity on William's part was only natural. But it was misdirected, as no documents have been found to imply that Maskelyne was indeed biased.

According to the rules of the trial, Maskelyne himself made determinations of local noon in Barbados by equal altitudes. His observations and those by others were later used in conjunction with Harrison's pre-declared rate in a set of calculations made by a group of four mathematicians. The results were reported to the Board (at a meeting to which the Harrisons were not invited) in January 1765, as well as the appointment of Nevil Maskelyne as Astronomer Royal. The results were much better than anyone expected: the average error of the watch was only 39.2 seconds, or the equivalent of one sixth of a degree of longitude. It was a phenomenal performance on the part of Harrison's watch.

Although the error of Harrison's watch was just one third that permitted under the terms of the Act for the entire prize, the Board withheld the award. Being cautious with the wording of the Act and realizing the huge importance of the situation in front of them, the Board held that they were not capable of judging whether the watch was "practicable and useful", in view of Harrison having not yet divulged its secrets. Furthermore, the lunar method was used on Maskelyne's return voyage from Barbados to predict the longitude of the Isle of Wight to within ten miles, and at the Board meeting Maskelyne provided evidence that the method had recently provided good results elsewhere. In order to secure Mayer's lunar tables for the Admiralty, the Board awarded £5000 to Mayer's widow. The Board then demanded that Harrison make a full disclosure in order to claim half the prize, and they additionally required that duplicates be made for testing before they would award the rest of the prize. They also stipulated that all of Harrison's sea clocks be made national property before dispensing the first half of the award. This of course was a severe insult to Harrison, coming at a time when patent laws were notoriously inefficient at protecting the rights of inventors, so he launched a public campaign denouncing the injustice he had been dealt. It was to no avail, however, as the Board remained silent and made no retractions from their decision.

Through a series of negotiations, the Board convinced Harrison they would protect his security as inventor, and in September 1765 Harrison was allowed to claim £7,500 (the first half less the £2,500 previously awarded). The next month he handed over his watch. In the following months he saw some of his secrets slip out through carelessness of the Board. The Board showed no penitence, but instead erected additional obstacles in front of Harrison in his quest for securing the second half of the prize. One was a ten-month long test of H4 at the Royal Observatory, after the watch had been dismantled and not properly adjusted. The watch had a drift rate of up to 19 seconds a day, which prompted Maskelyne to conclude that H4 was unreliable. The ensuing rounds ended with the Board awarding to Larcum Kendall (who had apparently worked with Harrison on the construction of H4) a contract to make an exact duplicate of H4, referred to as K1, while Harrison could do little else but proceed in making his own duplicate, H5. Kendall's watch was presented to the Board in January 1770, at which time Kendall expressed the opinion that H4 was constructed of parts prohibitively expensive for general application. He gained the backing of the Board to produce a more cost efficient watch. But K2 (which was taken on the voyage of the Bounty by Captain Bligh) and later Kendall watches lacked some of the features that made H4 so accurate, so they ended up giving unimpressive performances.

Kendall's first watch was sent on Captain Cook's second circumnavigation of the world (1772-1775), as well as inexpensive watches built by John Arnold. Cook had with him a team of experts proficient in the method of lunar distances, and from their results and the timekeeping of K1 (Arnold's watches failed to provide acceptable results), Cook concluded that it was indeed possible to use chronometers to fix longitude at sea to within 1½°, and usually better (WITHEY, 1987). Cook referred to Harrison's chronometer as "our never-failing guide" and "trusty friend" (BOORSTIN, 1985).

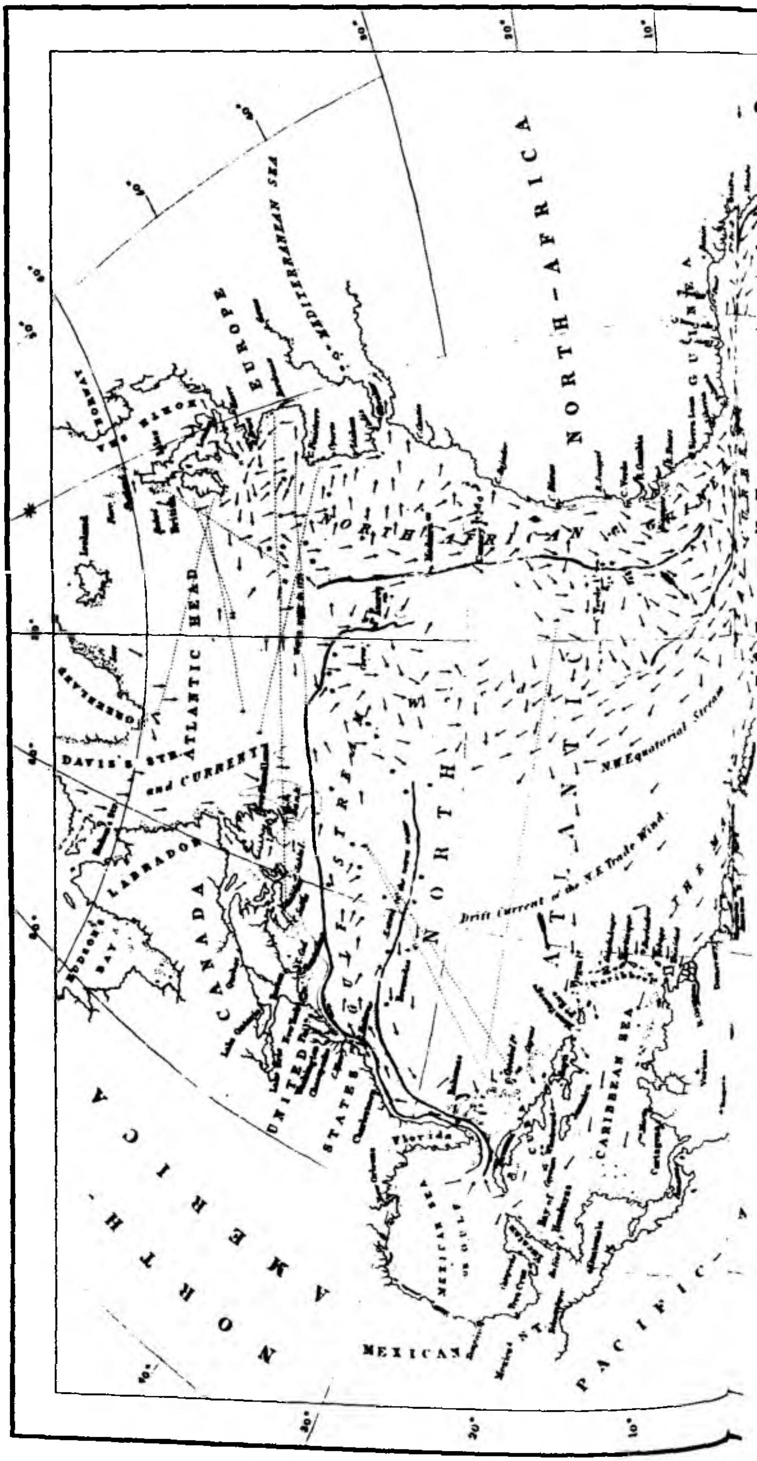
A severe problem facing Harrison was the Board's demand that he make at least two watches after H4, and that they would have to be satisfactorily tested before he could claim the second half of the prize. This was nearly impossible for him to do at his age, so he approached King George III and received favorable consideration. While Cook was at sea Harrison's fifth and last chronometer was tested at the King's private observatory in Richmond, and over a ten-week trial the error of H5 was determined to be just 4½ seconds. This was viewed as an unofficial trial not binding with the Board, but Harrison had completely discarded any thought of working through the Board. He opted to gain further support from the King and the support of other influential persons. Harrison filed petitions to Parliament, and after much political manoeuvering behind the scenes, apparently involving the King, Parliament declared that Harrison, at the age of eighty, after forty five years of work, be awarded all but £1,250 of the remaining prize.

Almost single-handedly, John Harrison demonstrated that accurate timekeepers could indeed be built for use at sea. His were extremely expensive to make, but it was not long after that John Arnold and other makers were providing more affordable chronometers to the maritime community. Their prices were still often more than the operators of merchant and whaling ships could afford, so improvements continued in the construction of ephemeris tables. In the late-eighteenth century small, inexpensive sextants were introduced that allowed for the simplified making of acceptable fixes with lunar distances. The method survived into the twentieth century. However, celestial navigation with the use of marine chronometers prevailed until radio and satellite navigation became available.

3.2. James Rennell and John Purdy – surface circulation of the Atlantic

In his opening remarks to *An Investigation of the Currents of the Atlantic Ocean and of Those Which Prevail Between the Indian Ocean and Atlantic*, published posthumously in the year 1832 by his daughter Jane, Lady Rodd, Major Rennell wrote (in 1820 according to the book's editor, Mr John Purdy): "Although the currents of the ocean form a most important part of Hydrography, yet it is only since the introduction of chronometers, and of celestial observations for the longitude at sea (that is, not much more than forty years ago,) that a competent idea of their direction and force, in any kind of detail, *could* be obtained."

Once chronometers came into use in the late eighteenth century, reliable observations of open-


NORTH AMERICA
NORTH AFRICA
EUROPE
MEDITERRANEAN SEA
NORWAY
Iceland
GREENLAND
DAVIS'S STR. and CURRENT
ATLANTIC HEAD
NORTH AFRICAN
NORTH ATLANTIC
GULF STREAM
LABRADOR
HUDSON'S BAY
CANADA
UNITED STATES
Florida
CUBA
MEXICAN SEA OR GULF
CARIBBEAN SEA
MEXICAN
PACIFIC
GUINEA
N.W. Equatorial Stream
Drift Current of the N.E. Trade Wind

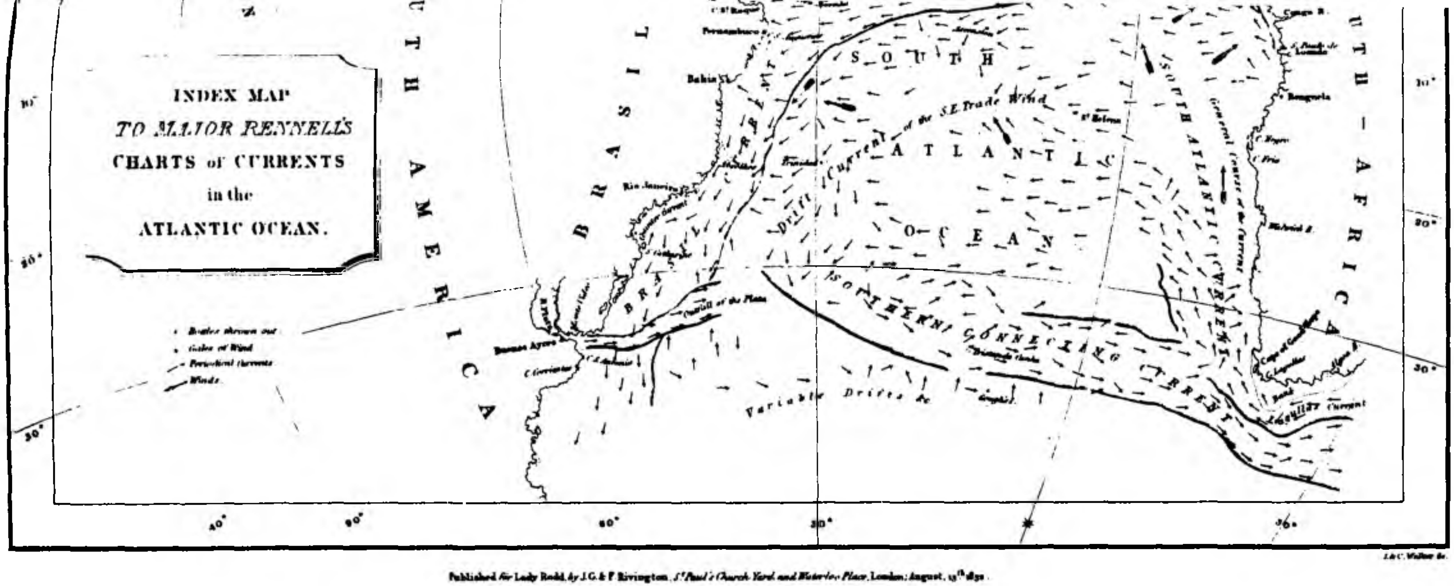


FIG. 12. Chart of surface currents in the Atlantic Ocean reproduced from *An Investigation of the Currents of the Atlantic Ocean, and of those which Prevail Between the Indian Ocean and the Atlantic* (RENNELL, 1832).

ocean currents began to accumulate in navigational records from much of the maritime world. During the final four decades of his life, Rennell conducted a personal project in which he systematically collected and reduced weather and current observations made at sea. It was a monumental undertaking for an individual, the first of its kind. In about the year 1810, Rennell drew a chart of currents in the Atlantic that he periodically adjusted through the years. Unfortunately, he did not live to see it published.

The making of this map was originally suggested to Rennell by his friend, the British hydrographer Mr John Purdy (1773-1843) (FINDLAY, 1853). Under Purdy's supervision, between the years 1812 and 1843, eight editions of sailing directions for the North Atlantic were published by the British Admiralty. Accompanying the sailing directions were charts whose primary roles were to show the most recent and correct geographical information; also included was information about the surface currents. On his first chart, PURDY (1812) showed the course of the Gulf Stream and gave remarks about it in the legend. The chart is rare (the only copy we have been able to locate is held by the British Museum) and it was drawn in portolan style on four sheets, each measuring about 90 cm on a side. The Gulf Stream was the sole current drawn on the map, in essentially the same position as it was on the Franklin-Folger chart.

Through the years, Purdy included in the sailing directions increasing numbers of narratives of currents in the Atlantic, mainly as they became available from ships' journals and often written by Rennell. For example, in the sixth edition, the last to be published while Rennell was still alive, PURDY (1829) credited several long passages to Rennell. How much Rennell drew in turn from Purdy's collection of materials we do not know, for Rennell only discussed the observations made at sea without citing previous authors or contemporary investigators. The key differences between the writings of Purdy and Rennell are that Purdy most often gave summaries of specific observations whereas Rennell attempted to merge the observations into a more general overview, and that Rennell was more inclined to provide theories for what was observed. Judging from Purdy's extensive assemblage of observations, it is nearly certain that he was one of Rennell's major sources of information. To wit: in concluding the advertisement (preface) to RENNELL 1832), Lady Rodd wrote: "To Mr John Purdy I feel under great obligation; my Father's high opinion of his talents induced me to select him to be the Editor, and the judicious manner in which he has executed his trust has more than justified my confidence".

RENNELL (1832) considered an attempt to deal with the World Ocean as being too great an undertaking in his advanced age, so he restricted his treatment of currents to "the principal streams of current in the North and South Atlantic Oceans; and those which pass between the Indian and South Atlantic Oceans, round the Cape of Good Hope: ..." He used the best measurements available to him to objectively arrive at a general, interconnected system. He also attempted to give causes for the various currents, often using explanations proposed earlier by others such as the winds being the "prime movers" of the ocean. He further drew a distinction between two kinds of currents, and this distinction became commonplace in oceanographic thinking for several decades to follow. The two types of currents central to his ideas were a "drift" current, produced by local winds, and a "stream" current resulting from an accumulation of a drift current along an obstacle, such as land or a stream current already formed (the term "Gulf Stream" was no doubt influential to his definition of a stream current). As had been generally accepted for more than a half century, he wrote of winds producing elevations on the sea surface, which to him was most spectacularly demonstrated by the continual action of the trade winds driving water into ever smaller confines in the Caribbean Sea and then the Gulf of Mexico, thus leading to a downhill flow of a uniquely intense Florida Current.

RENNELL's (1832) great contribution was to advance significantly the descriptions previously given by VOSSIUS (1663) and DE BRAHM (1772) about the large-scale interconnections between the surface currents. This work proved to be a landmark since in it a wealth of new information was synthesized for the first time. It was immediately hailed by his contemporaries and served as a foundation upon which subsequent developments would be built for decades to come. Shown in Fig.12 is RENNELL's (1832) summary map of surface currents in the Atlantic Ocean. While many of the currents in the North Atlantic had already been identified and described in detail, those in the South Atlantic had not. Because this was the first comprehensive description of currents in the South Atlantic, it might thus be considered the more important element of the book; we will focus our attention on it.

A pair of remarkable observations made by Rennell before he discussed the individual currents comprising the large-scale circulation were that "on the whole, the waters have a greater tendency towards the middle of the North-Atlantic than otherwise," and "it is unquestionable that there is one and the same line of current from the Cape of Good-Hope, north-westward, towards and through the West-Indies and Strait of Florida; and occasionally home to the shores of Europe". In this way the net northward flux of surface water across the equator in the Atlantic was described. Rennell was perplexed by this seeming mass imbalance, and he speculated that it might be associated with enhanced evaporation in the Mediterranean Sea and in regions warmed by the Gulf Stream. He was on the right track, but he made no speculations about a deep circulation that could balance the net northward flow of surface water. It would seem that he was unaware of Rumford's papers dealing with the properties of fluids (Section 2.5.5), or at least the significance of them. Modern estimates for the net northward surface flux are around ten Sverdrups ($1\mathrm{Sv} = 10^6.\mathrm{m}^3.\mathrm{s}^{-1}$), which is balanced by the deeper thermohaline circulation (e.g., ROEMMICH, 1983).

Rennell began his descriptions of currents with those near southern Africa, "the highest point up the stream." Reiterating his observations made in the 1770s, the "Lagullas Current," he said, is born out of the confluence of the Madagascar and Mozambique Currents, the latter being "by much the strongest," in the region along the Indian Ocean coast between Durban and Port Elizabeth. From there, the main body of the current, being "at least 100 fathoms in depth," flows along the edge of the Agulhas Bank toward the south, while a smaller portion fans out over the bank toward the west and southwest. More recent observations of currents and temperature (made in 1819-20) by Captains Hamilton, Alsager, and Wilson led Rennell (his page 98) to accede, "It was formerly thought, by most persons, that the entire body of the Lagullas stream passed round or over the bank to the westward, into the Southern Atlantic; but it now appears evident that the greater part returns back into the Indian Ocean, ..., merging with the well known easterly current that issues from the South-Atlantic". The Agulhas Current retroflection, as it is now called (BANG, 1970), was in this way explicitly described, probably for the first time. The rate of transfer of Indian Ocean water into the Atlantic around the southern terminus of Africa is now thought to be less than ten Sverdrups, or about a tenth of the total Agulhas Current transport (PETERSON and STRAMMA, 1991). Within the region of retroflection, Rennell noted that great eddies and irregularities are to be found, an observation in concordance with our present knowledge of that region having the highest levels of eddy kinetic energy anywhere in the southern hemisphere (e.g., PATTERSON, 1985). However, the retroflection does not appear on Rennell's chart, probably because his manuscript was not yet ready for publication when he died.

Regarding the part of the Agulhas Current escaping retroflection, Rennell described it as meeting and uniting with other flow to form a wide current running at one to one and a half miles per hour toward the northwest as far as 25°S. There Rennell found it to blend into the northwestward current produced by S.E. trade winds, which together flow equatorward as the "South Atlantic Current." He described his South Atlantic Benguela Current (now simply called the Benguela Current) as flowing north along the western coast of Africa all the way to the equator before turning sharply west to become the Equatorial Current. However, inspection of his summary chart reveals no significant flow along the western coast of Africa between the latitudes of about 10°S and 30°S. The northward flow is depicted as separating from the coast at roughly 30°S, very much in line with what can be seen in modern illustrations of the Benguela Current region (e.g., Stramma and Peterson, 1989). Rennell did not discuss this feature, possibly because he would later argue that relatively cool water at the equator is a result of the South Atlantic (Benguela) Current bringing in water from a colder southern latitude. Had he instead attributed the equatorial coolness, at least in part, to the vertical convection scheme proposed by Rumford (1797), he may have had more room for discussion.

After it turns westward at the equator, Rennell described the flow as becoming wider through the entrainment of water, mainly from the southeast, set in motion by the trade winds. The Equatorial Current was thus explained as extending farther south of the equator than north. According to Rennell, the Equatorial Current splits twice, once when a branch veers off to the northwest near 23°W, and again when the current reaches the eastern tip of South America. With the latter splitting, at Cape St. Augustine (near 8°S and present-day Recife), the main portion of the current flows north around Cape St. Roque and then along the northeastern coast of Brazil, ultimately entering the North Atlantic. The lesser portion, "which the author will beg leave to call the Brasil Current," turns south. The first splitting, near 23°W, is no longer observed, but the latter is, and Rennell's description of it is similar to how Vos had described it nearly two centuries before. The important difference is that Rennell could see that the southward turning branch is the weaker of the two. This is substantiated by present-day analyses and it may be a reason for the conspicuous weakness of the northern Brazil Current when it is compared with other western boundary currents (Stramma, Ikeda and Peterson, 1990).

Judging by his words, it would seem that Rennell invented the term "Brazil Current." At its point of origin, he described this current as being "of inconsiderable breadth till, increased by the accession of drift current by the SE Trades, it arrives in 16°S or 17°S, where, to the distance of 250 miles from the coast of Brasil, the current runs to the south of south-west, and gradually declines to the southward till it becomes south-south-west, or nearly alongshore to Cape Frio (23°S), where its rate was found to be 30 miles per day, at 200 miles from the shore." Southward from Cabo Frio to Santa Katarina (27½°S), a northward-flowing countercurrent was found inshore of the Brazil Current, and from there the Brazil Current continued south to the region of the outlet of Rio de la Plata. "Here the remarkable circumstance of the passage of the current of the Plata, across and over the southerly current, takes place: beyond which, to the south, the Brasil current again appears, and is felt all the way to Staten Land (off the eastern tip of Tierra del Fuego), although slow". Rennell attributed knowledge of the cross current from the river mainly to Captain Beaufort, while the southward extension of the Brazil Current all the way to the southern tip of South America was said to be well known and that "It appears to continue to Cape Horn itself, and even to turn round it into the Pacific Ocean". This southward extension of the Brazil Current all the way to, and then around, Cape Horn is not shown on his summary chart, and may have been based on second-hand communication instead of actual data.

The last of the major currents in the South Atlantic according to Rennell "may, perhaps, be properly named the Southern Connecting Current," which he considered to be "the connecting current of the South-Atlantic, with the Pacific and Indian Oceans, round the Cape of Good Hope and Cape Horn. This stream arises from two sources. The first and most powerful is a portion of the drift water from the S.E. trade, detaching itself from the Brasil current; and the other the drift water of the prevalent westerly winds beyond the trades". He conceded that the region of westerly winds in the middle South Atlantic was not well known, but that there is "probably a derivative of the Brasil current,about latitude 39°, which Captain Beaufort traced eastward from thence to about 22° of longitude running, on the whole, east, at a mean rate of 18 miles per day; but there he lost it. It is known that a constant drift or slow current runs to the east or E.N.E. from the island of Tristan da Cunha; and, indeed, every circumstance proves that there is a general motion to the east between the parallels of 30° and 40°S, and which, when it arrives near the Cape of Good Hope, is a very wide and strong current; strong enough to run 2000 miles beyond the Cape". Earlier in the book he said the Agulhas Current is turned back toward the east and is traceable for forty degrees of longitude into the Indian Ocean between 35° and 40°S, whereas the current from the Atlantic is turned back toward the northwest, mixing with the small amount of Indian Ocean water escaping the Agulhas retroflection. This is the more accepted of the two explanations, and again it seems as though Rennell was not able to bring his book into self-consistency before his death.

From this it appears that the earliest discussion of the current associated with the South Atlantic Subtropical Front (Convergence) was made. Consistent with present information (e.g., STRAMMA and PETERSON, 1990), Rennell described it as extending east from the Brazil Current along about 40°S. It also appears that Rennell considered the major flow to the south of South America as being eastward, although he had earlier proffered that the Brazil Current rounds Cape Horn in the other direction. This becomes a bit less clear when he said, "Concerning the Antarctic region, we know but little; whether it be land or sea; but Captain Cook always found currents running from thence to the northward. Those will naturally be referred to the melting of the ice and snow, in summer: it was only during that season, that he had any opportunity of gaining information. But if there be no great portion of land, and the ice be all floating, the author is at a loss to understand how (such currents could exist)." The northward set experienced by Cook was presumably the result of Ekman surface drift, which was unknown at the time and is to the left of the winds in the southern hemisphere (mainly eastward in the latitudes Cook sailed). The implication is that Rennell favored the idea of a continuous eastward current in the Southern Ocean as opposed to a northward one, and his appears to be the first attempt to describe the Antarctic Circumpolar Current.

For the North Atlantic, RENNELL (1832) described the branch of the Equatorial Current running along the northern coast of South America as entering the Caribbean between the Antilles and weakening considerably before continuing on into a large clockwise circulation in the Gulf of Mexico and then to finally run downhill with the Florida Current. Rennell devoted more than a hundred pages to the Gulf Stream, and some of the more important observations have been summarized by STOMMEL (1965). A seemingly minor, but in truth quite important, feature to note on his map is a set of arrows denoting westward counterflow just south of the Gulf Stream. This is the earliest portrayal of it that we know about, and it is a feature that was included in many subsequent maps of the era. It did not survive far into the twentieth century and it is absent from modern theories of the wind-driven circulation, but as REID (1994) states in reference to the Gulf Stream return flow there, "it is an inescapable result in any plausible treatment of the geostrophic shear".

Other currents in the North Atlantic discussed by RENNELL include the Arctic (Labrador) Current, known long before by William Bourne (TAYLOR, 1963), the North Atlantic Current, which Rennell described as being north of the Gulf Stream and having a slow eastward drift probably as a result of the westerly winds, and a southward current in the eastern basin "which flows continuously, though irregularly, in point of direction, from our (British) parallels to the coast of Guinea and Bight of Biafra, at all times; and in some seasons, to five degrees south of the Equator."

The large-scale circulation of the North Atlantic was fairly well known by Rennell's time; we therefore do not discuss in any further detail his lengthy descriptions of this basin. It would probably be true, however, that an in-depth analysis of his accounts there would reveal many facts pertinent to present-day research, just as his accounts of the South Atlantic are presently relevant. The great breadth of Rennell's study of the entire Atlantic Ocean, truly unprecedented, must accordingly be remembered as the era's seminal piece of work – as it was an invaluable model for subsequent researches into the surface circulation of the World Ocean.

3.3. Alexander von Humboldt; Emil von Lenz – on density variations

A younger contemporary of Rennell was Alexander von Humboldt (1769-1859), a German geographer and naturalist who made significant contributions to a wide range of subjects. His contributions to oceanography began on a five-year (1799-1804) scientific journey to the Americas, during which time he sent back letters that were published in French and Spanish periodicals, then later in a Berlin monthly, all achieving great success. In the Americas, he made measurements of the Peru Current (HUMBOLDT, 1837) and the Gulf Stream (HUMBOLDT, 1816). Although the Peru Current was known long before (e.g., VARENIUS, 1650), Humboldt was the first to make scientific observations of it. For this reason, the current is often referred to by his name (BERGHAUS, 1837a; and many others). His first measurements of the current, made in September 1802, showed its surface water as being 7°C colder than the water farther off-shore. He thought the coolness of the current was a result of it having a southern source and he attributed the cool coastal climate to the current, as opposed to local opinion that maintained the climate was the result of snow cover on nearby mountains (HUMBOLDT, 1837).

More than two decades after his return to Europe, in 1828, Humboldt acquired Rennell's data (KORTUM, 1990) and for the remaining three decades of his life he worked on a manuscript entitled (translated), *On Ocean Currents in General and on the Cold Peruvian Current in the Pacific in Contrast to the Warm Gulf- or Florida-Stream.* This manuscript was unfinished and unpublished at the time of his death and was subsequently lost. It has recently been found, but is not yet generally available (KORTUM, 1990). There are no maps of ocean currents accompanying this manuscript.

The most famous of Humboldt's works is *Kosmos. Entwurf einer physischen Weltbeschreibung* (outline description of the physical world), which consists of five volumes based on lectures he delivered in 1828 and 1829 at the Singakadamie in Berlin. In the first volume, HUMBOLDT (1845, pp. 326-330) gave a broad account of ocean currents, including the "Equatorial or Rotation Current," which he attributed to the progression of high tide (similar to some ideas from two centuries earlier) and, as others from the previous century had done, to the prevailing trade winds. He also described differences in sea-water density at various latitudes and longitudes, resulting from temperature and salinity variations, as being important to the movements in the ocean, though he elaborated little on this.

Humboldt's comments on the importance of density differences derived from the pioneering work of Count Rumford on the properties of water and from the work of the Russian physicist Emil von Lenz (1804-1865). During Kotzebue's voyage to the Antarctic in 1823-1826 on the *Rurik*, Lenz made a series of temperature and specific gravity measurements, the most extensive and reliable of the period. During that voyage, LENZ (1830; 1832) found a zone of low salinity lying along the equator, highest salinities a few degrees of latitude on either side of the equator, and low salinities again at higher latitudes. Later, LENZ (1845) noted the low temperatures found beneath the surface in the equatorial belt and concluded they, and the low salinities there, were the result of upwelling of deeper waters as required by the conceptual model put forth by Rumford. He considered this to be the motivating force for movements in the ocean, which would then be modified by Earth's rotation and the action of surface winds.

There are no detailed descriptions of currents in *Kosmos*, probably because of Humboldt's ongoing work with his manuscript on ocean currents that was never finished. But much of the material assembled for it in the early years, including the data base Humboldt procured from Rennell, was available to a close associate, Heinrich Berghaus. Owing to Humboldt's initiatives, Berghaus would go on to make contributions to physical oceanography on a level of importance approaching that of Rennell's.

3.4. Heinrich Berghaus – global surface circulation

Heinrich Berghaus (1797-1884) was a German geographer and cartographer in a long line of individuals who made Justus Perthes' cartographic institution in Gotha renowned. Among Berghaus' many achievements was his five volume treatise on geography *Allgemeine Länder- und Völkerkunde*, first published in the year 1837. In it, BERGHAUS (1837a) gave the earliest comprehensive descriptions of global ocean currents based on information revealed by maritime chronometry (though many of the descriptions were borrowed, with due credit made, from Humboldt's unpublished materials; similar descriptions can also be found in *Almanach für das Jahr 1837* (BERGHAUS, 1837b)). To complement his treatise on geography, and at the earlier request of Humboldt in 1827 (ENGLEMANN, 1964), BERGHAUS (1845) put together a thematic collection of maps illustrating the world's physical geography. It was the first collection of its kind and continues to be emulated by present-day atlases. It was entitled *Heinrich Berghaus' Physikalischer Atlas*. Contained in this atlas are charts of currents for the Atlantic and Pacific, prepared in the year 1837, and one for the Indian Ocean prepared in 1840. As a set, these charts were the first to show the global ocean circulation (outside the polar regions) in a completely empirical way. They were left unchanged in a revision of the atlas (BERGHAUS, 1852), with the sole exception being the removal from the Pacific chart of the name of a countercurrent (Mentor's Gegen Drift) from the region off northern Chile.

3.4.1. Atlantic Ocean. In comparing Berghaus' chart of the Atlantic (Fig.13a) with Rennell's, it is clear that Berghaus relied heavily on Rennell's work, as acknowledged by Berghaus in the explanatory note inserted over central Africa. Aside from the more elaborate artwork, only a small number of changes were made by Berghaus. The large-scale patterns shown by Rennell were left essentially unchanged; the major currents were given the same names (in German) and were shown in the same locations with the same orientations and spatial scales. The only significant change made to Rennell's depiction is that of a retroflection now drawn in the Agulhas Current south of Africa with only a small part of the current leaking into the Atlantic, just as Rennell had described in his book. For the flow that re-enters the Indian Ocean, Berghaus used the German equivalent of "Return Current," which is still in use today. There are also a small number of additions made by Berghaus, these including a northward current next to western Greenland, an anticyclonic circulation in the Gulf of Mexico, the labelling of the countercurrent off-shore of the Gulf Stream, and an inset showing ship-drift measurements in the northern Drake Passage - Patagonia region.

The domain of the Falkland (Malvinas) Current was mentioned only briefly by BERGHAUS (1837a, pg. 539) when he said that the northward drift from the "Cape Horn Current" provides a second source to the South Atlantic Connecting Current (the first being the Brazil Current). In Berghaus' map, the outflow from the Rio de la Plata is broader than in Rennell's, and here it has a second branch. BERGHAUS (1837a) elaborated on this, saying that the eastward outflow of the river can be felt for nearly 600 miles east and northeast of the coast. He was unaware of the true magnitude of the confluence between his two sources of the Connecting Current and the intense eddy field produced there as a consequence. This notwithstanding, he was the first to identify the northward flow of the Falkland Current. KRÜMMEL (1911, pg. 607) cited a "very rare" chart with the English title, *Sailing Directory for the southwestern part of the Atlantic Ocean, constructed by Henry Berghaus, Potsdam, July 15, 1841*, upon which appears the remark, "in this track (just north of the Falkland Islands) the Drift Current runs for the most part of the year northerly from Cape Horn". Indeed, the existence of a "Cape Horn Current" off the southern tip of South America, flowing continuously from the Pacific into the Atlantic, had only recently been established by the "lamented" Captain Henry Foster in 1828-30 (FINDLAY, 1853; MÜHRY, 1872).

3.4.2. Pacific Ocean. The earliest chart of ocean currents for the Pacific, outside of the speculative maps by KIRCHERI (1664/5) and HAPPEL (1685), was published in Paris by the French sea captain Louise Isidore Duperrey (1786-1865) in the year 1831. It was entitled, *Carte du mouvement des eaux à surface de la mer dans le Grand Océan austral*. This became a very rare chart and not even KRÜMMEL(1887), despite his efforts, was able to see one. It has, however, been found in the Service historique de la Marine in Vincennes by P. Hisard in 1992, who has generously provided us with a clear photograph of it and who has since reproduced portions of it (HISARD, 1993). This chart spans the area between 20°N - 65°S and 135°E - 45°W, thus including the southwestern South Atlantic. It consists of the tracks of ten expeditions beginning with Cook's second voyage (1773) and ending with Beechey's second (1828), and along the tracks are arrows showing directions of the observed currents. These arrows are too small to remain clear in a reduction, so we do not reproduce the chart here.

The same current arrows were included in the chart drawn in the year 1837 and published in 1845 by Heinrich Berghaus (Fig.13b). BERGHAUS (1845) also used additional data, largely from Prussian trading cruises. The geographical domain of Berghaus' chart extends northward beyond the Hawaiian Islands (then known as the Sandwich Islands) to the Arctic, making this the first complete map of the Pacific.

BERGHAUS (1837a) began his discussions of the Pacific Ocean by acknowledging that it was much less understood than the Atlantic. He then printed a lengthy account of the Peru Current (pp. 575-583) as Humboldt had written it in his unpublished manuscript. Following this, Berghaus (p. 584) used the term "Humboldt Stromung" for what is identified on his chart as the "Peruanische Stromung". In drawing a parallel with the naming of "Rennell's Current" in the Atlantic, Berghaus reasoned that it would be appropriate to use Humboldt's name in referring to the Peru Current, and he was probably the first to do so.

Humboldt made his initial descriptions of the Peru Current shortly after the turn of the nineteenth century. His observations were substantiated in different seasons by Duperrey, von Holmfeldt and Meyen in the years 1823, 1825 and 1831, respectively. According to Berghaus, Humboldt's opinion of the current having a southern source was expanded upon by Duperrey on the basis of additional ship drift observations made with marine chronometry. Duperrey's new view of the South Pacific circulation included the earliest account of the northern portion of the Antarctic Circumpolar Current in the Pacific sector, not then recognized as part of a zonally-continuous flow. Duperrey identified the South Pole (Antarctica was not yet mapped) as being the source of a current formed from melted ice and drifting under the influence of winds; he thought this current flowed NNE from its source to the longitude of the southern cape of New Zealand, and then to gradually curve so that it flowed ENE by the time it reached the longitude of Pitcairn Island (130°W of Paris on Fig.13b). From there the current was described as continuing to the western coast of South America between Conception and Valparaiso, whereupon it split into two branches. The southern branch supplied the Cape Horn Current whereas the Peru Current was formed out of a part of the northern branch that hugged the coast. The remainder of the northern branch was described as turning back toward the west under the influence of the trade winds to feed into the Equatorial

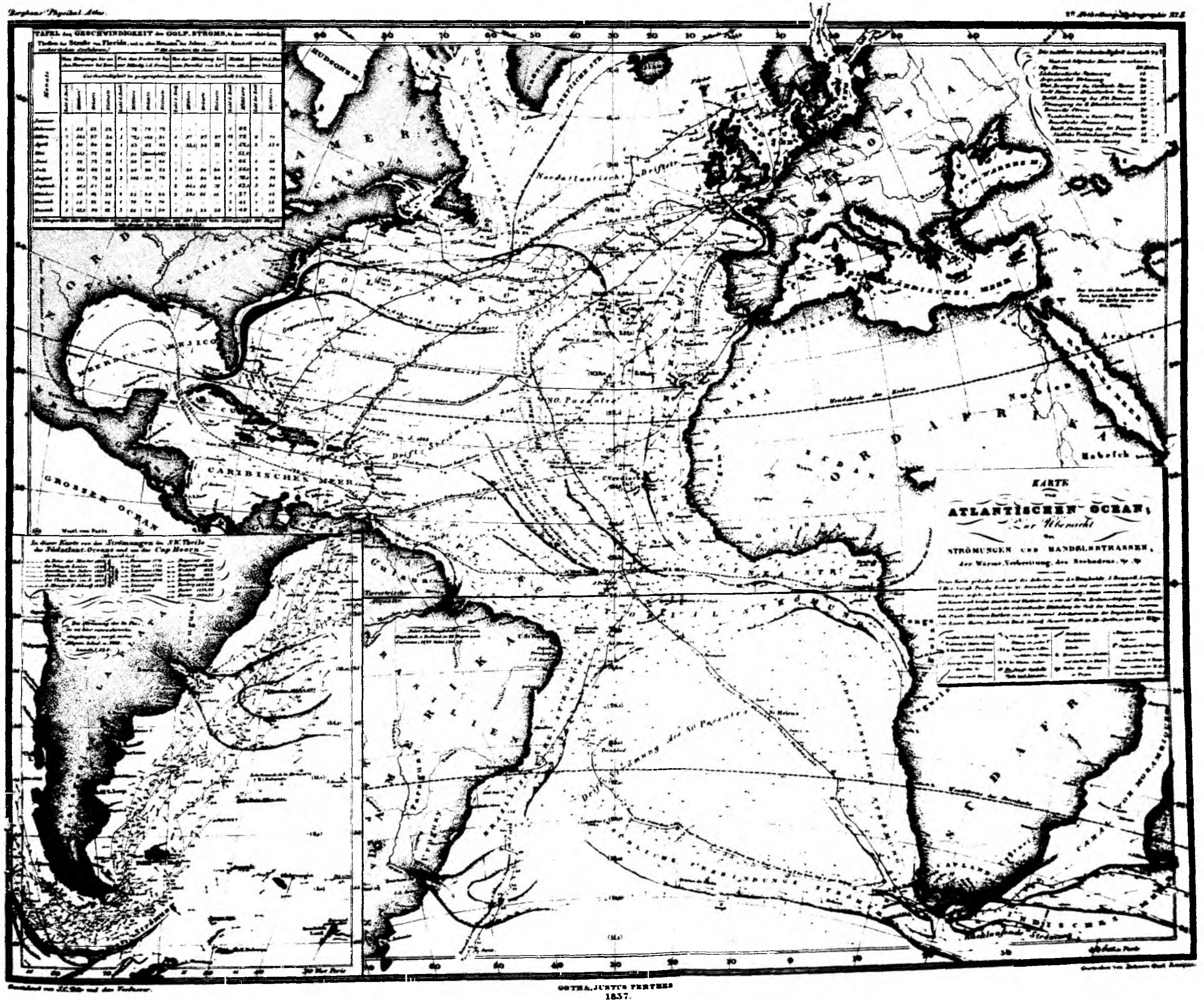


FIG.13(a). Chart from 1837 of surface currents in the Atlantic Ocean reproduced from the

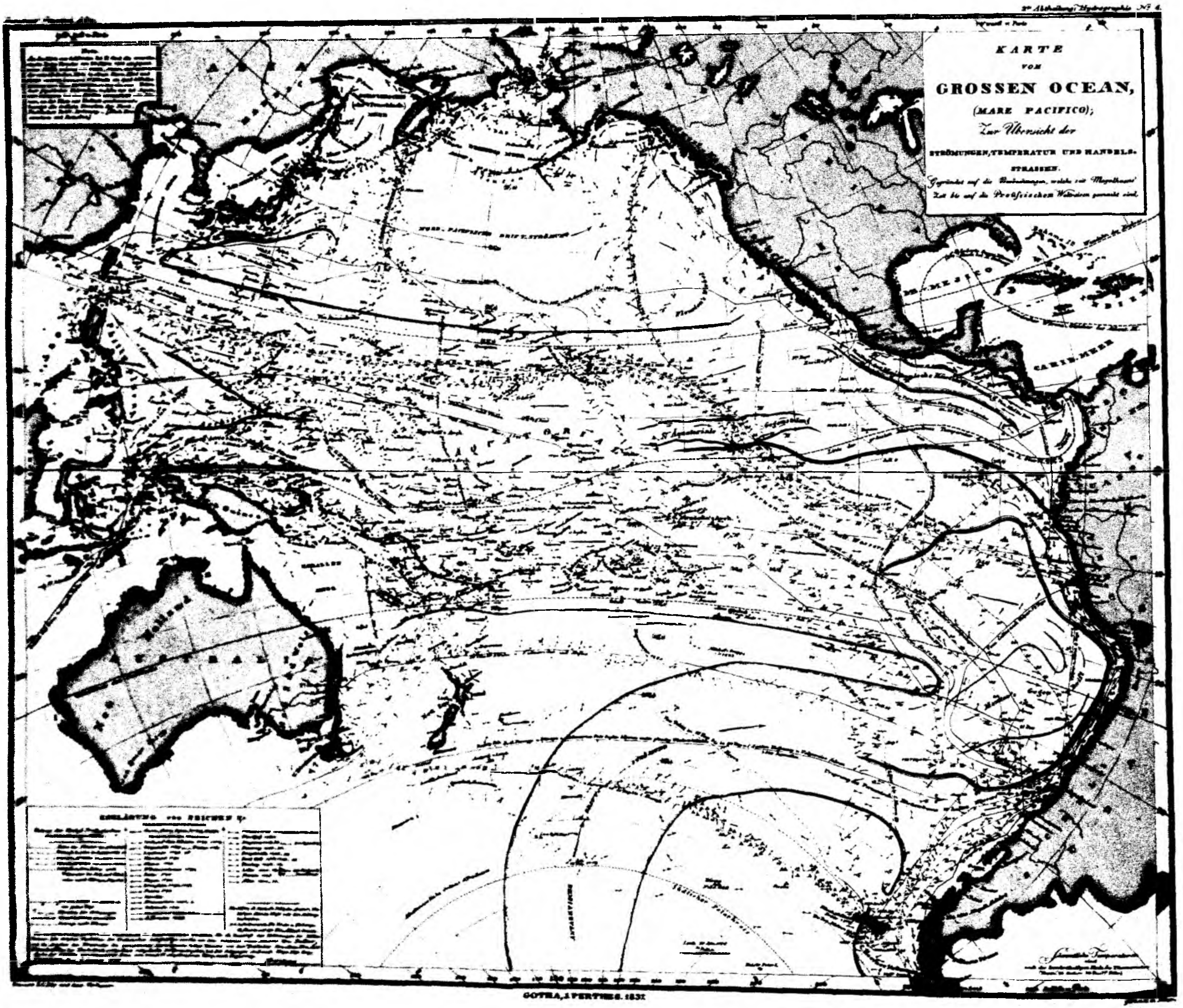


FIG. 13(b). Chart from 1837 of surface currents in the Pacific Ocean reproduced from the *Physikalischer Atlas* (BERGHAUS, 1845).

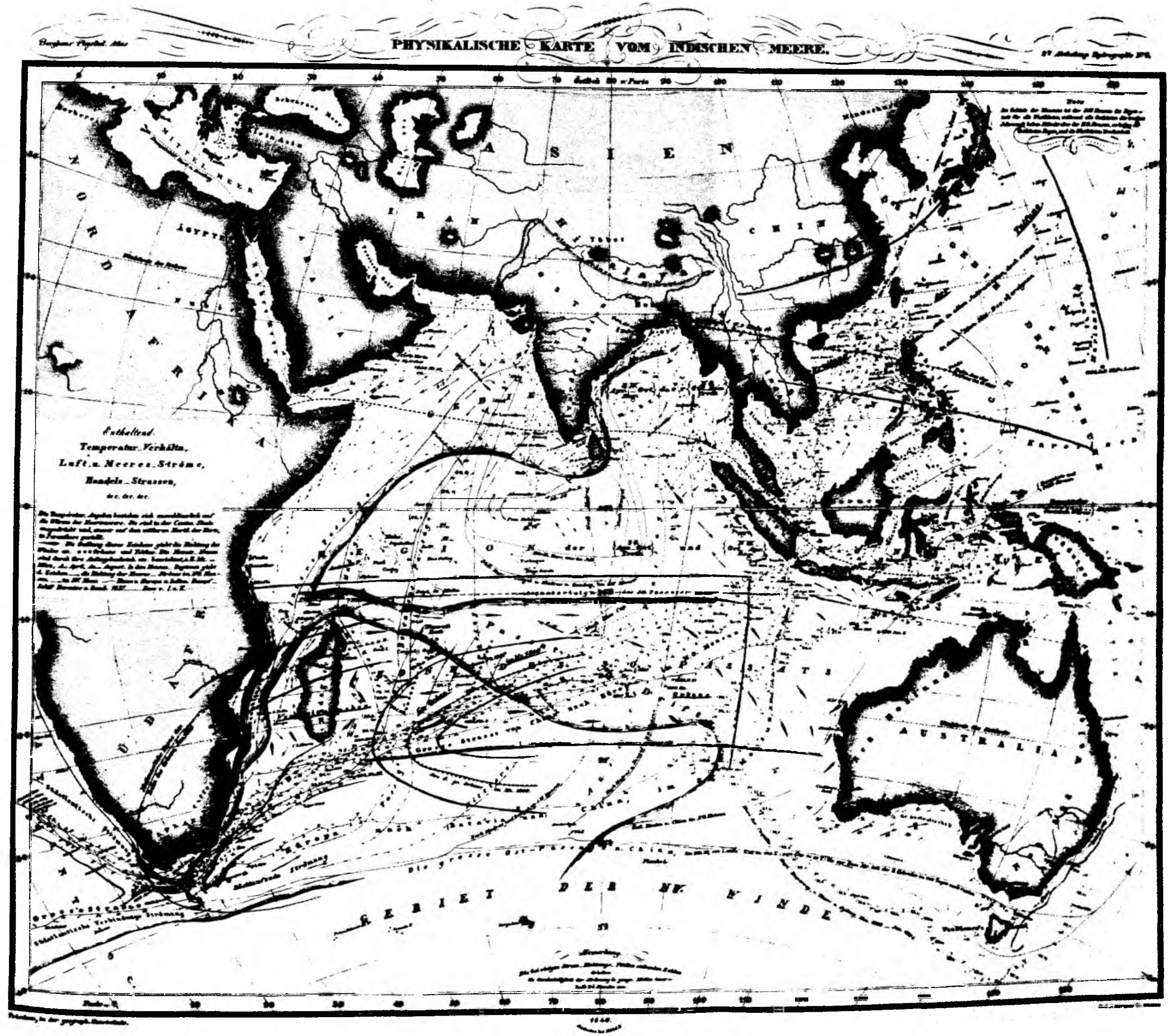


FIG.13(c). Chart from 1840 of surface currents in the Indian Ocean reproduced from the *Physikalischer Atlas* (BERGHAUS, 1845).

Current, which Duperrey considered to lie between the latitudes of 26°S and 24°N. Berghaus showed all these features on his chart.

An important feature shown on Berghaus' chart and only briefly mentioned in the text is the North Equatorial Countercurrent. Berghaus said he noticed it while assembling information from Prussian trading cruises, and he seems to have thought it was connected with eastward flow that had been reported to the west of Hawaii by Captain Krusenstern. Details on the chart, which do not survive in the reduction, show that what is labelled the North Equatorial Counter Current was observed on cruises by the *Mentor* in 1823, by the *Princess Louise* in the years 1826-8, 1831, and 1833, and by the *Senjawin* in 1826-9. Berghaus obtained his information from the original ships' logs, to which Duperrey had no access and thus did not include on his map, so Berghaus' depiction of the North Equatorial Countercurrent in the Pacific was the first to have been made for any equatorial countercurrent in the world. (According to HISARD (1993), there had been reports of eastward surface drifts in the equatorial Pacific and Atlantic from eighteenth century circumnavigations, but the concept of general westward motion combined with inadequate navigation prevented the reports from being accepted).

Also not shown on Duperrey's map is what Berghaus called the Japan Current. We do not know just when this current was discovered, but it was well known by the time of VARENIUS (1650) and was likely known long before to the Japanese, who Captain BEECHEY (1831, pg. 240) said were calling it the "Kourosi-gawa", or current of the Black Gulf. Recall that it may have been shown on charts as early as the 1540s by Battista Agnese (Section 2.3.2). Berghaus, though, was probably the first to describe this current as originating from the large-scale westward flow in the tropics, citing several observations. An extension of the Kuroshio Current into the North Pacific is not shown on Berghaus' chart, as there were very few observations from the regions north of the trade winds. He related, though, how in the year 1804 Captain Krusenstern had found a current toward the northeast on a cruise from Hawaii to Kamchatka, and deduced that there must be a northeastward drift in view of the fact that parts of Japanese ships had been found on the American coast.

Farther north, BERGHAUS (1837a) made no mention of currents in the Sea of Okhosk, where southward flow is indicated on the chart, nor along the eastern coast of the Kamchatka Peninsula. He briefly described currents in the Bering Sea, saying that Admiral Burney (who had sailed as a lieutenant with Captain Cook) expected a closing of the region between Asia and America because of the "quiet" sea. Later voyages showed the existence of an ocean current in the Bering Strait; Captain Kotzebue found a NE current along both the Asian and American coasts, while Beechey later observed the current to be only about 4 fathoms deep. Berghaus also made no mention of the Alaska Current, which is indicated by arrows along the Gulf of Alaska, but he did note that along the American northern coast the flow is toward the northwest. The Alaska Gyre was thus weakly implied by his descriptions and by the patterns on his chart. Also not commented upon was "Fleurieu's Wirbel," named after the French sea captain and depicted near 140°W of Paris. The California Current is not shown on the map, but Berghaus described how Romme had observed a permanent southward current along the California coast. From there Berghaus described the "Mexican Coastal Current" (along the southern Mexican and Central American coast) as flowing toward the southeast in the months of December to April and toward the northwest from May to December, the reversal being caused by monsoon winds.

Berghaus concluded his discussions of the Pacific Ocean with currents in the western tropics. For the region south of the western Caroline Islands, he noted that a strong eastward current had been observed in June and July, which Krusenstern said could be found up to 6° north of the equator. South of the equator at these longitudes Berghaus thought there were indications of a westward current, but the many island groups there appeared to interrupt the trade winds and the connected currents. Irregular currents were also described in the region around New Holland (western Australia) and between New Zealand and New South Wales (eastern Australia). A narrow current was drawn on Berghaus' chart along the eastern coast of Australia, which was described as flowing toward the south-southwest from August to April, but with the more off-shore flow toward the north-northeast. The current along the coast was thought to reverse during the three winter months. Also seen to reverse with the seasons were the currents near southern China, which Berghaus said were strongly dependent on wind, mainly the monsoon winds.

3.4.3. Indian Ocean. It is ironic that while the Indian Ocean was the first to have been routinely navigated, by Arabs after the fall of the Roman Empire (Section 2.2), and was the first to have its major currents discovered, that it was the last of the three major oceans to have its currents charted. To our knowledge Berghaus was the first to do so. Shown in Fig.13c is the 1840 version of his Indian Ocean Chart (BERGHAUS, 1845), which is identical to the second version drawn in 1849 and published in 1852. Unlike his charts for the Atlantic and Pacific oceans, this one also contains wind information.

BERGHAUS (1837a, pg. 600) made a remarkable observation (translated): "The Indian Ocean, which in its southern regions is connected with the Atlantic and Pacific oceans, appears to receive from the latter an inflow made possible by the Agulhas Current, in the great oceanic valley, transferring important amounts between the Old and New worlds". He supported this with an overview of the currents in the northern Indian Ocean responding to changing winds, while those in the southern (tropical latitudes) swept continuously from east to west. As previously described, RENNELL (1832) knew of the net transfer of surface water from the South Atlantic to the North, and he was certain that it was balanced by Indian Ocean water coming round the Cape of Good Hope. Here Berghaus extended the concept by saying that the flow into the Atlantic is compensated by a transfer from the Pacific into the Indian Ocean, but without saying where the transfer should take place nor offering an explanation for how the balance in the Pacific should work. The eastward flow south of Cape Horn (illustrated on Berghaus' Atlantic and Pacific charts) must have prevented him from saying more about inter-ocean exchanges. Knowledge of the deep circulation was still a long way off, and the existence of a southern continent and a continuous current around it were also unknown. The information needed to give further explanations simply did not exist, but what was available pointed to there being inter-oceanic exchanges on a global scale, a topic we now agree as being central in understanding the global energy balance.

Berghaus went on to describe the monsoon reversals of currents in the northern Indian Ocean, which had long been known but not yet described in detail (VOSSIUS, 1663) had attempted to do so). According to Berghaus, a northward current along the Coromandel coast (eastern India) appears in February with the start of the southwest monsoon and reaches its maximum strength in May. The northward current then decreases in strength and disappears in October. By November, during the northeast monsoon, the flow along eastern India is strongly southward and continues to the southern end of Ceylon (Sri Lanka) where it turns west toward the Maldives. During the southwest monsoon the flow is in the opposite direction. Along the Malabar coast (western India) in March and April it is strong toward the southeast, turning southwest at the Laccadives (Lakshadweep). From May to September there is a current into the Persian Gulf, and out during the other months. From the equator northeastward along Africa and then along the Arabian coast is a northeast current that begins with the southwest monsoon in March and April and continues until September or October when the monsoon changes. The flow then reverses toward the southwest and continues into the southern hemisphere to the Mozambique Channel, where the southward current is permanent. The trade winds were described as causing the Mozambique Current, which is relatively weak during the southwest monsoon and strong during the northeast.

In the southwestern Indian Ocean, Berghaus depicted the South Equatorial Current (Trade Wind Drift) as feeding almost entirely into the narrow current flowing through, but not entirely filling, the Mozambique Channel. Berghaus thought the current might be toward the north in the eastern side of the channel, an acceptable observation now. Farther south on the chart, a weak flow is depicted as coming from the south of Madagascar and entering the Agulhas Current, which in turn is shown as largely retroflecting back into the Indian Ocean while part of it rounds the Cape of Good Hope, as in his Atlantic chart. However, unlike the Indian Ocean chart that shows the Mozambique Current as being far stronger than the Madagascar, the Atlantic chart indicates an opposite situation that would be more acceptable now. With respect to the retroflection, Berghaus described the return flow as becoming eastward at about 40°S, but that it was still unclear if it is favored by westerly winds. He suggested a closure to the subtropical gyre in the South Indian Ocean when he mentioned observations made by Flinders, who sailed east from the Cape of Good Hope along 37°S and found a continuous eastward current (the South Indian Ocean Current (STRAMMA, 1992)) splitting into two flows near Australia. One branch moved north along the west coast of the continent whereas the other went along the southern coast.

3.4.4. Additional comments. The work of Heinrich Berghaus, and thus the influence of Alexander von Humboldt, spread rapidly beyond German borders. Even before the first *Physikalischer Atlas* appeared in 1845, the charts of currents drawn by Berghaus in the years 1837-40 had already been reproduced in an atlas by the English geographer Alexander Keith Johnston (1804-1871) (JOHNSTON, 1843). Shortly afterwards, a graduate student studying under Berghaus, August Heinrich Petermann (1822-1878, who would eventually go on to establish the well-known journal *Petermann's Geographische Mittheilungen*), travelled to England to work with Johnston, and while there he published his own atlas (PETERMANN, 1850). It contains a single-page consolidation of Berghaus' three charts, with the patterns on it being copied nearly verbatim from Berghaus but without ship tracks and current arrows. Later, JOHNSTON (1854) again reproduced Berghaus' charts, without the ship tracks and arrows and with all entries and titles shown in English; no citations were made or acknowledgements given to Berghaus.

In concluding his descriptions of ocean currents, BERGHAUS (1837a) drew a lengthy and eloquent quote from Humboldt's unpublished manuscript, part of which translates as: "The ocean currents are brought about by continuously blowing winds, differences in specific gravity which depend on heat or salt content of the water, variations in barometric pressure, through accumulation of water (as in the Mexican Current) or disturbance of the level, through strong evaporation (as in the Mediterranean), which are finally demonstrated by the existence of a great variety of cleaved icebergs (a reference to cross sections of ice indicating climatic variations). The direction of the currents are variously modified through the configurations of coasts, through the rotation of Earth, as a water particle progressing toward the equator or toward a pole can assume the rotational velocity of each degree of latitude only gradually, and through winds and countercurrents. It is the task of physicists to determine, and continuously improve (their estimates of), the numerical proportions of those elements (the prime causes of motion and its disruption) upon which the ocean and the atmosphere depend, though following the model of the astronomical sciences is admittedly unattainable it will at least lead to a knowledge of some of the eternal laws which bring about climatic changes in the construction of currents in the fluid envelope of our planet".

This passage was presumably written in the early 1830s, and in it Humboldt reflected a growing respect for the complexity of oceanic motions and that the role of the ocean in climate is not static. These concepts had been expressed earlier by Waitz, Rumford, Rennell and others, but the effect of Earth's rotation in deflecting oceanic flow had been accorded little importance. As we have seen, Maclaurin wrote in 1740 that Earth's rotation could deflect meridional oceanic flow, but also that his brief and general remarks, obscurely published, drew little attention to the matter. At


MAP
of the
CURRENTS
and
WHALING GROUNDS
West Coast
East Coast
New Holland
Icy Barrier
Icy Barrier
Antarctic Continent
Enderby Land

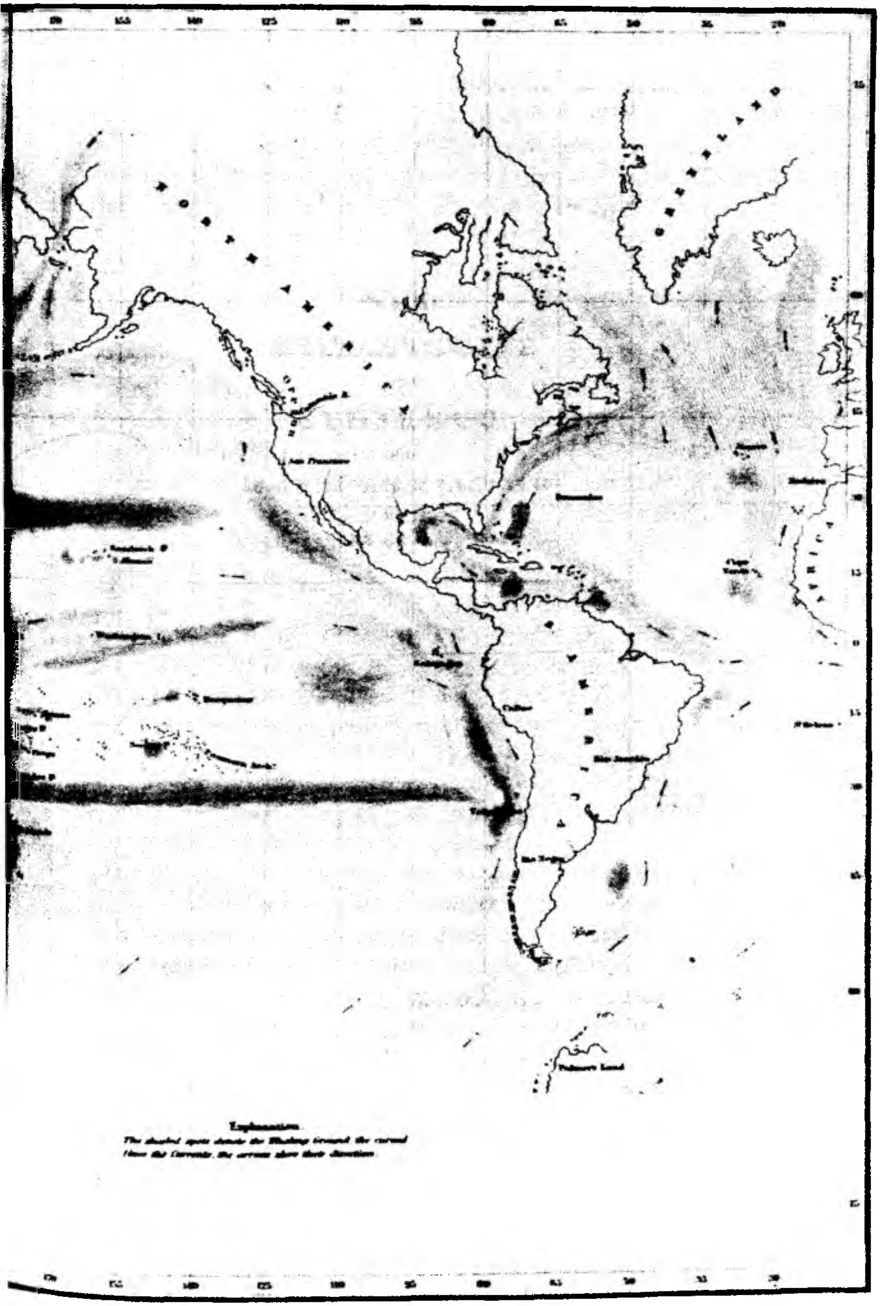


FIG.14. World chart of surface currents by WILKES (1845).

Humboldt's writing it was not yet known that a deflection of zonal flow also exists, though it could be seen in the LAPLACE (1778) tidal equations, and it would remain unknown until its discovery in 1856 by William Ferrel (Section 3.9).

By the time Berghaus published his descriptions, the primal role of wind in driving the surface circulation was coming to be questioned. In 1836, Francois Arago reported (according to KOHL, 1868) that a team of French engineers had worked their way across the Florida peninsula and found that the maximum difference in sea level that could exist between the east coast and the west was just 7½ inches. This seemed to Arago to be much less than what was needed to propel the Gulf Stream at its observed strength, so he proposed that Earth's rotation was the most important factor and that it would combine with differential heating and cooling to produce the zonal currents. Like Maclaurin in 1740, Arago apparently made no attempt to explain any specific currents. He instead suggested that Hadley's theory for the trade winds be modified for the oceanic circulation.

BERGHAUS (1837a) limited all his discussions to the surface flow, and the quote he published from Humboldt makes no explicit reference to deep circulation, though Humboldt had already written elsewhere about the idea offered by RUMFORD (1797) of deep equatorward currents originating from polar latitudes (WARREN, 1981). The opinion was also forming that the cold Labrador Current could sink and flow south beneath the Gulf Stream. This idea was based on observations made off the Grand Banks of Newfoundland of icebergs moving south with the Labrador Current and continuing south for some distance after encountering warm waters of the northeastward-setting Gulf Stream; the icebergs would continue moving south until the Gulf Stream had deepened to the point where its flow would become the dominant force and carry the icebergs away from the undercurrent. According to FINDLAY (1853), W.C. Redfield made a report of this in 1838, which was published by the American Philosophical Society in 1843. The idea gained quick acceptance (WILKES, 1845) and in 1845 Professor A.D. Bache assumed on theoretical grounds the existence of a polar current underlying and running counter to the Gulf Stream, and he even proposed an experiment to detect it (PILLSBURY, 1891).

3.5. Charles Wilkes – global circulation: surface, subsurface

By an Act of U.S. Congress in May 1836, the outfitting of a naval expedition was authorized for the purpose of exploring and surveying parts of the Atlantic, Southern, and Pacific oceans. Because of the importance of American commercial whaling interests, the Southern Ocean was identified as being the region of greatest concern. The "United States Exploring Expedition" was thus born, the first American scientific mission conducted abroad.

The expedition faltered for nearly two years because of poor organization and administration, so in March 1838 the Secretary of the Navy assigned command of the operation to Lieutenant Charles Wilkes (1798-1877), who had been in charge of the navy's Depot of Charts and Instruments. The whole expedition was organized anew, and in August 1838 a squadron of five ships sailed from Norfolk. Included in the squadron's scientific equipment were 29 of the finest English chronometers, which were to be used for navigation and the estimation of surface currents. The technique of using current logs was also employed, but Wilkes doubted their importance owing to large, inherent inaccuracies.

After the conclusion of the expedition in 1842, and after facing a court-martial that resulted in a public reprimand for his illegal punishment of some of his squadron members, Commander WILKES (1845) published a five-volume account and an atlas of the expedition's activities and scientific observations. He reserved nearly all his descriptions of ocean currents for the fifth volume, where, instead of describing just those that were encountered on the expedition, he provided a general account of oceanic circulation and a global map (Fig.14). The locations of commercially viable whaling grounds were also discussed and indicated on the map as the shaded areas.

In his narrative, Wilkes mentioned the Rennell Current, and like Rennell, Wilkes drew a distinction between permanent flows and local ones, which he termed streams and currents, respectively. It is likely that Wilkes had knowledge of the contents of Rennell's book, though he made no mention of it. However, it is doubtful that he knew of the contents of Berghaus' narrative. Had this been the case, Wilkes would have probably repeated some of Berghaus' information in justifying certain features of the circulation, which he did not. But because Berghaus' maps had been reproduced and widely distributed by A.K. Johnston in London, and Wilkes no doubt had access to them in Washington, the Pacific and Indian Ocean portions of Wilkes' map were probably not drawn on an entirely independent basis. The style of presentation used by Wilkes, however, appears to be his own invention. Sets of parallel lines, resembling modern streamlines, were used to indicate the large scale patterns of what Wilkes referred to as the "general circulation." This style of portrayal, and the term, are still in popular use today.

In addition to differentiating between "streams" and "currents", Wilkes further categorized these flows as being of polar or equatorial origin, and he discussed at length indirect evidence for subsurface polar flows. As noted in the previous section, he presented evidence for the existence of a subsurface polar stream moving opposite and beneath the Gulf Stream, and shortly afterward in the narrative he proposed the existence of a polar subsurface stream in the eastern tropical North Atlantic. This was based on low temperatures recorded at depth, and he attributed strong surface currents he observed near the Cape Verde Islands to the action of subsurface currents impinging on the islands and raising the local sea level. He wrote: "Beyond the Cape de Verdes, overfalls, rips, and a continual tendency to change in the surface of the ocean are experienced, as if two great conflicting submarine currents were meeting at some depth beneath the surface". The importance Wilkes placed on subsurface flow is also seen throughout his narrative in a similar context for other islands and for unusual occurrences in the open ocean. He seems to have been unaware of Rumford's theories about a thermohaline circulation, especially because Wilkes believed the ocean depths were filled with waters having temperatures near 4°C, the temperature of maximum density of freshwater.

Wilkes attributed the existence of a wind-opposing eastward current observed north of the equator in the Atlantic, first observed near 5°N; 58°W by Colonel Edward Sabine in 1822 while sailing on the *Pheasant* (according to Wilkes), to a subsurface current originating from an elevation of sea level along the northern coast of Brazil (the combined effects of Earth rotation and meridional variations in eastward wind stress would ultimately come to be acknowledged as the cause). Other observations of the Atlantic North Equatorial Countercurrent were made in the following years (HISARD, 1993), but this feature was not included on the earlier maps by Rennell or Berghaus. Wilkes' depiction of it appears to be the first for the Atlantic.

Wilkes was dissatisfied with theories about wind driving the Gulf Stream. He found it difficult to imagine that the relatively gentle trade winds could pile up so much water in the west that a current with the power of the Gulf Stream could be created, and he was equally skeptical that winds could produce permanent currents anywhere. He was unable to formulate a clear alternative theory at the time, but he suspected that temperature differences were important. When the Gulf Stream is warmer, he said, it would become stronger, and conversely, the Labrador Current would strengthen upon becoming colder. It seems doubtful that he knew of the measurements of sea level on the opposite coasts of Florida that were reported by Arago in 1836 (in the relatively obscure German journal *Poggendorff's Annalen der Physik und Chemie*), as Wilkes made no reference to

Arago nor to Arago's conviction in the importance of Earth's rotation.

By disclaiming the wind-driven theory, Wilkes could speculate anew about the height of the subtropical gyre and he came closer to the truth than others before him, though his reasoning was flawed. He contended that the Gulf Stream could not be responsible for the huge masses of weed found in the Sargasso Sea, as had been long supposed, but rather that it grows there. He based this on there having been very few other drift objects found in the region. He also contended that the general set of currents was outward from the middle of the Sargasso, thus indicating a higher level of the sea surface. He suggested that there was a higher sea level in the middle of the subtropical gyre, and his map is surprisingly good with respect to the westward location of the gyre's center and the attendant appearance of a Gulf Stream return flow to its south and east. The eastward extension of the Gulf Stream, however, was not drawn toward northern Europe, which could have been done considering the temperature measurements made in previous decades showing a branch oriented toward England and which Wilkes gave credit for the unusually mild climate enjoyed by England at its high latitude. But neither Rennell nor Berghaus had shown it on their maps either, perhaps because the rapidly-varying winds and surface drifts in the region led to a confusing set of reports. With the exception of the Labrador Current, the northern North Atlantic circulation was drawn in ways inconcordant with present descriptions. Note, however, that the Loop Current in the Gulf of Mexico is clearly shown, as filling the entire gulf, which Berghaus had indicated with only a small set of arrows.

For the South Atlantic, Wilkes drew analogies between the system of currents there and those in the North, and he made an exceptionally competent description for his era of the confluence between the Brazil and Falkland Currents. He reported that the southern extension of the Brazil Current shifts off-shore of the cold, northward-flowing Falkland Current before turning east to supply warm water to the interior of the basin. The cold current was described by Wilkes as "the Patagonian Current, a branch of the Great South Polar Stream, that comes round Cape Horn, and sets along the coast of the country whence it is named". He attributed the cold upwelling waters off Cabo Frio to the Patagonian Current, and he described this branch of the Cape Horn Current as turning north around the eastern side of the Falkland Islands. His rationale was based on numerous reports of icebergs advected north along that path, and the occasional occurrence of large expanses of ice just east of the islands while the near-coastal areas always remained free of ice. On his map there is a broad confluence of the southward moving waters of the Brazil Current and the northward flow of the Falkland Current, the first such depiction of this dynamically important phenomena, and it was drawn where we now see it at about 40°S latitude. As with the Labrador Current meeting the Gulf Stream, Wilkes believed that a portion of the cold water of the Falkland Current sinks and continues equatorward beneath warmer water at the surface. WÜST (1935) presented a similar viewpoint, but the descending water now appears to move off toward the east (REID, 1994). Wilkes also removed the large outflow from the Rio de la Plata that Berghaus had shown.

Although the Southern Ocean was the most politically important region for the expedition, Wilkes' accounts of its currents were relatively scant. He contended that northeastward flow issued from the Antarctic, as Captain Cook had earlier said, and where it met with warmer waters it would submerge and continue along its course. But instead of considering this flow to be uniformly distributed around the Southern Ocean, Wilkes thought there were individual streams that split after impinging upon the southern terminus of Africa, the southwestern corner of Australia, southern New Zealand, and the southern tip of South America. This was done to accommodate measurements made with deep-sea thermometers showing cold water at depth in these regions, and this explains the seemingly confused patterns drawn on the map. Where the flow appears to cross is where Wilkes thought the subsurface and surface currents were in different directions. An item of interest about the surface currents is that Wilkes observed the strongest ones in his voyage through the Southern Ocean near Macquarie Island, which is now known to be near the high-speed cores of the Antarctic Circumpolar Current. Sailing farther south toward the Antarctic continent, Wilkes observed the currents to gradually diminish, as they generally do. He was unable, however, to make current measurements at and near the ice edge because of mechanical and navigational problems.

In the Pacific Ocean, Wilkes identified the continuity of the Peru Current with the South Equatorial Current, which he believed to become very weak or non-existent in the middle of the ocean, and then the South Equatorial Current feeding into the East Australia Current. He compared the latter with the Gulf Stream, observing it to be "much less remarkable" than its counterpart in the North Atlantic, while noting that warm water from the East Australia Current could sometimes be found south of Van Diemen's Land (Tasmania), as we presently observe. (Berghaus had not shown the complete continuity, nor did he think the current along eastern Australia always flowed south). In the tropics, Wilkes made an exceptional description of the North Equatorial Countercurrent as: "This last tropical counter-current was traced by us between the same parallels (4°N and 9°N), nearly across the Pacific, from the longitude of 170°E, to the longitude of 138°W. We had no opportunity of ascertaining ourselves whether it exists to the westward of the Mulgrave Islands, but Horsburgh and several other authorities mention the prevalence of an easterly current as far to the west as the Sea of Celebes, and particularly in the latitude of 4°N". This led him to think that the origin of the countercurrent was in the Indian Ocean and to show the Indonesian Throughflow (as it is now called) as going in the opposite direction now recognized. Farther north, Wilkes made mention of the North Equatorial Current, however because of extremely small sets in his navigation between Hawaii and the Caroline Islands he formed the opinion that there were no substantial currents in the region. He thus did not show a continuity of the North Equatorial Current with the Kuroshio Current, in which case Berghaus' representation was the better. But Wilkes was apparently the first to draw the Kuroshio extension as going all the way across the Pacific to eventually feed into the southward flow of the California Current.

For the far north Pacific, Berghaus had earlier mentioned the possibility of northward flow through Bering Strait, but Wilkes was now making clear statements about it and he was the first to clearly portray it on a chart (though he showed it as direct branch from the Kuroshio). The arrow on the map indicating southward flow from the strait was described as a subsurface flow that Wilkes thought could not amount to much. Regarding the northward surface flow, Wilkes again provided a surprisingly insightful interpretation. According to him, relatively warm surface water flows from the Pacific through Bering Strait into the Arctic Ocean where it is cooled by the polar atmosphere before finding its way into the northern North Atlantic where it then sinks beneath the warmer Gulf Stream waters. Such spillage over the northern sills into the Atlantic and their subsequent sinking are now well documented (e.g., REID, 1994).

Wilkes provided just a short account of the Indian Ocean circulation, likely because his squadron made a rapid transit through the southern portions of it, and perhaps because he did not attach the same significance to it as he did the other two oceans. South of Africa, the Agulhas Current was not described as retroflecting back into the Indian Ocean. He described warm surface waters as flowing swiftly southward through the Mozambique Channel and southwestward over the Agulhas Banks, and then he had the Agulhas Current diffusing toward the southwest. He maintained that the warm surface flow was a shallow feature not as important as a deeper flow of cold water coming from the south. The remainder of the Indian Ocean was drawn in a manner similar to what Berghaus had drawn. Although Wilkes mentioned the monsoons in the north he made no attempt to deal with them in the text or on the map.

The accounts given by Wilkes represent the era's third significant advance in describing the oceanic circulation, after those given by Rennell and Berghaus who did not consider the deep circulation. Wilkes' viewpoint was a clear extension of their's – that the prevailing motions of the ocean do not come about as an aggregation of unorganized responses to regional influences, but rather that certain basic patterns obtain, with necessary variations, in all three major oceanic basins. Wilkes provided a particularly germane example when he pointed out: "In taking a general view of the facts which have been stated, it will appear that, towards the western sides of the North and South Atlantic, of the North and South Pacific, and of the Indian Oceans, streams of heated water, making their way from low to high latitude, prevail". He did not explicitly say that these warm currents are also among the strongest in the world, but his narrative made it obvious. The modern concept of western intensification was beginning to appear.

Considering the number of new, and usually improved, descriptions of the surface circulation provided by Wilkes, the recognition he has received is inordinately small. The primary reason might be that his section on currents in the *Narrative of the United States Exploring Expedition* was not read by a wide audience, though it had been publicly distributed. We have seen few citations made to it by contemporary and later authors. Perhaps this in turn was because of the overshadowing personality of Lieutenant M.F. Maury that would soon arrive on the scene. Another reason for the quiet reception of Wilkes' work may be that his theoretical explanations were weak and poorly supported. He placed a great deal of importance on presumed submarine currents, much more so than did his predecessors and peers, but he scarcely mentioned how the density of sea-water is influenced by temperature and salinity. He also disputed the prevailing thinking about the importance of wind in causing ocean currents in general and the Gulf Stream in particular, and he provided as an alternative only the vague idea that temperature differences were somehow the cause. A few years later, when the effects of Earth's rotation were being considered more seriously, Captain WILKES (1859) argued that instead of causing significant deflections of flow, the important effect of Earth's rotation was the greater centrifugal force produced in the tropics than at mid latitudes. This would result in an accumulation of water in the western tropical Atlantic that would in turn drive a downhill-rushing Gulf Stream. It was a variation of similar explanations given in the Renaissance, and since these had long since fallen from favor Wilkes' theory was little noticed.

3.6. *Charles Philippe de Kerhallet – global surface circulation*

The practical problems of wind and ocean currents on navigation had become increasingly well known throughout most parts of the world in the few years following the work of John Purdy in England. A French sea captain, C.P. de Kerhallet (1809-1863), was engaged at the Dépot Général de la Marine in the late 1840s in the task of assimilating new information into an improved set of sailing directions for all three oceans. He presented his first complete set of results in a trio of papers (KERHALLET, 1850, 1851a,b), and soon thereafter expanded his treatment of the Atlantic (KERHALLET, 1852). Like Purdy, Kerhallet also provided descriptions and charts of ocean currents to accompany his sailing directions (Figs 15a-c).

Kerhallet's mode was to relay the patterns of circulation as they had become known, making few references to physical theory. In the early part of his discussions about currents in the Atlantic he did mention what others had been thinking, but thereafter he seldom brought it up. His citations to previous investigators were also sparingly made, which, as the works we have dealt with indicate, was not unusual. Among other citations, he did refer to Rennell, and to the 'savant' Berghaus (scholarly or masterly) through the cartographical reproductions given by Johnston. He

CARTE DES COURANTS GÉNÉRAUX DANS L'OCÉAN ATLANTIQUE.

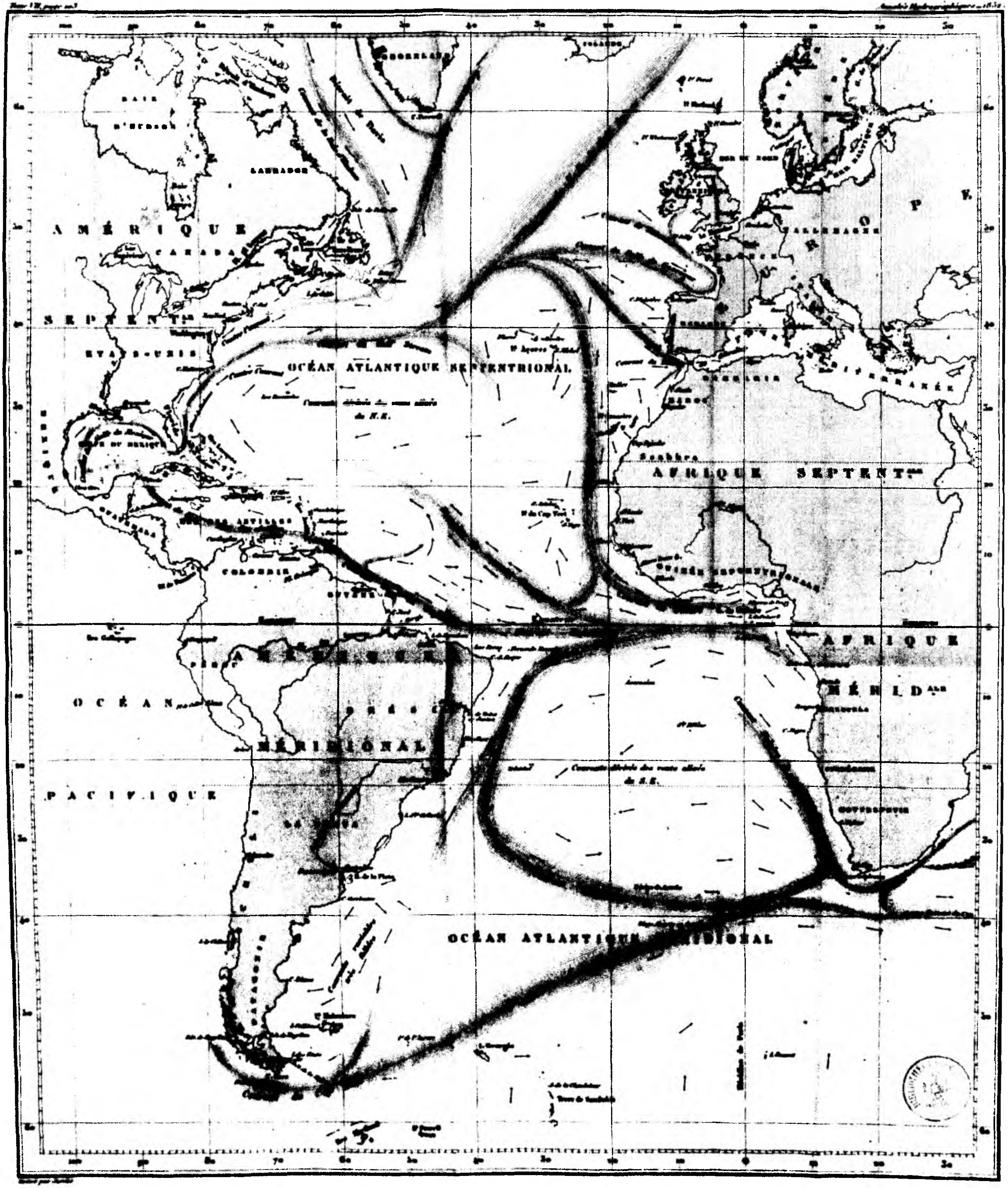


FIG. 15(a) Chart of surface currents in the Atlantic Ocean by KERHALLET (1852). The current patterns are identical to those in an earlier chart by KERHALLET (1850).

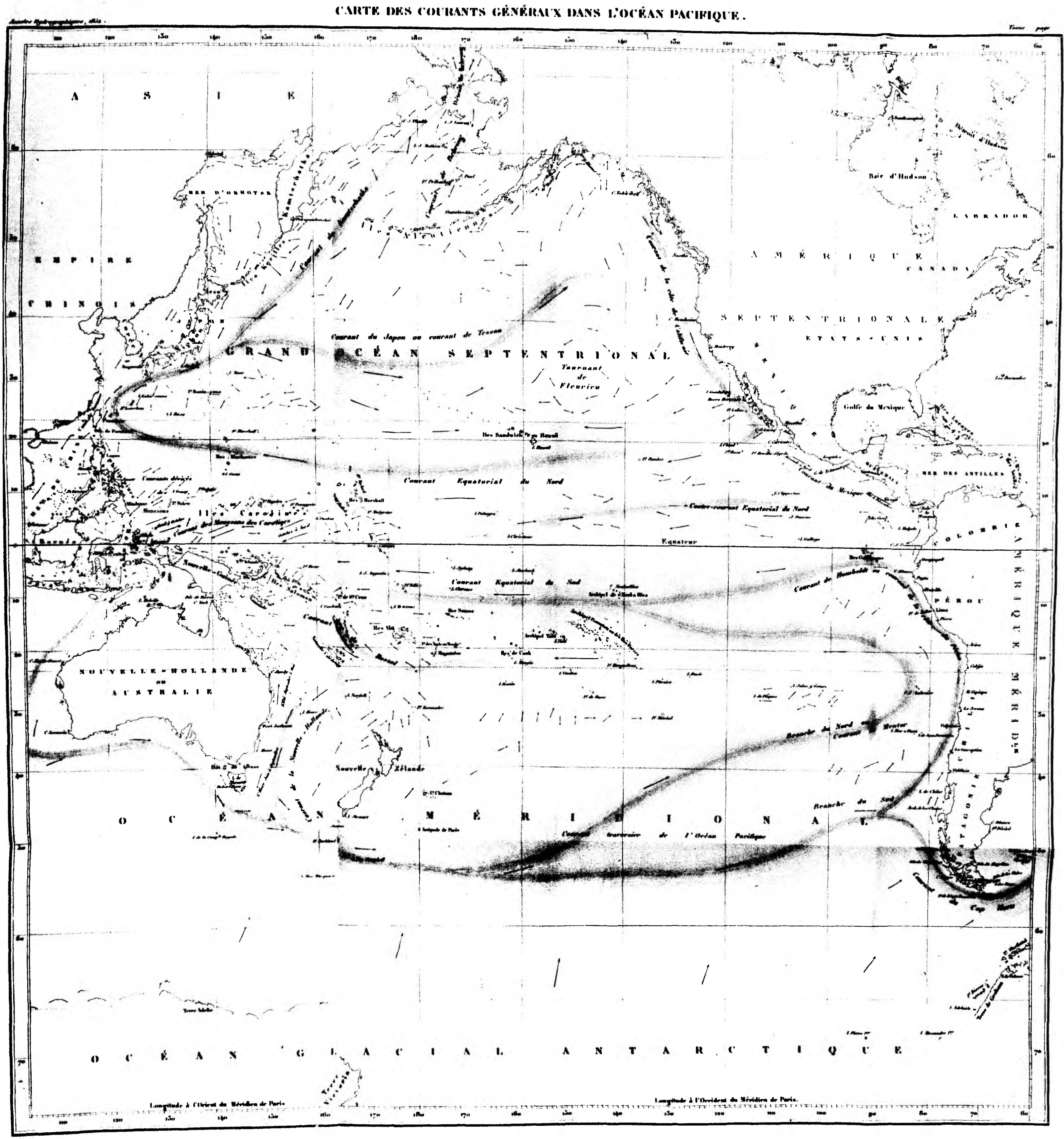


FIG.15(b). Chart of surface currents in the Pacific Ocean by KERHALLET (1851b).

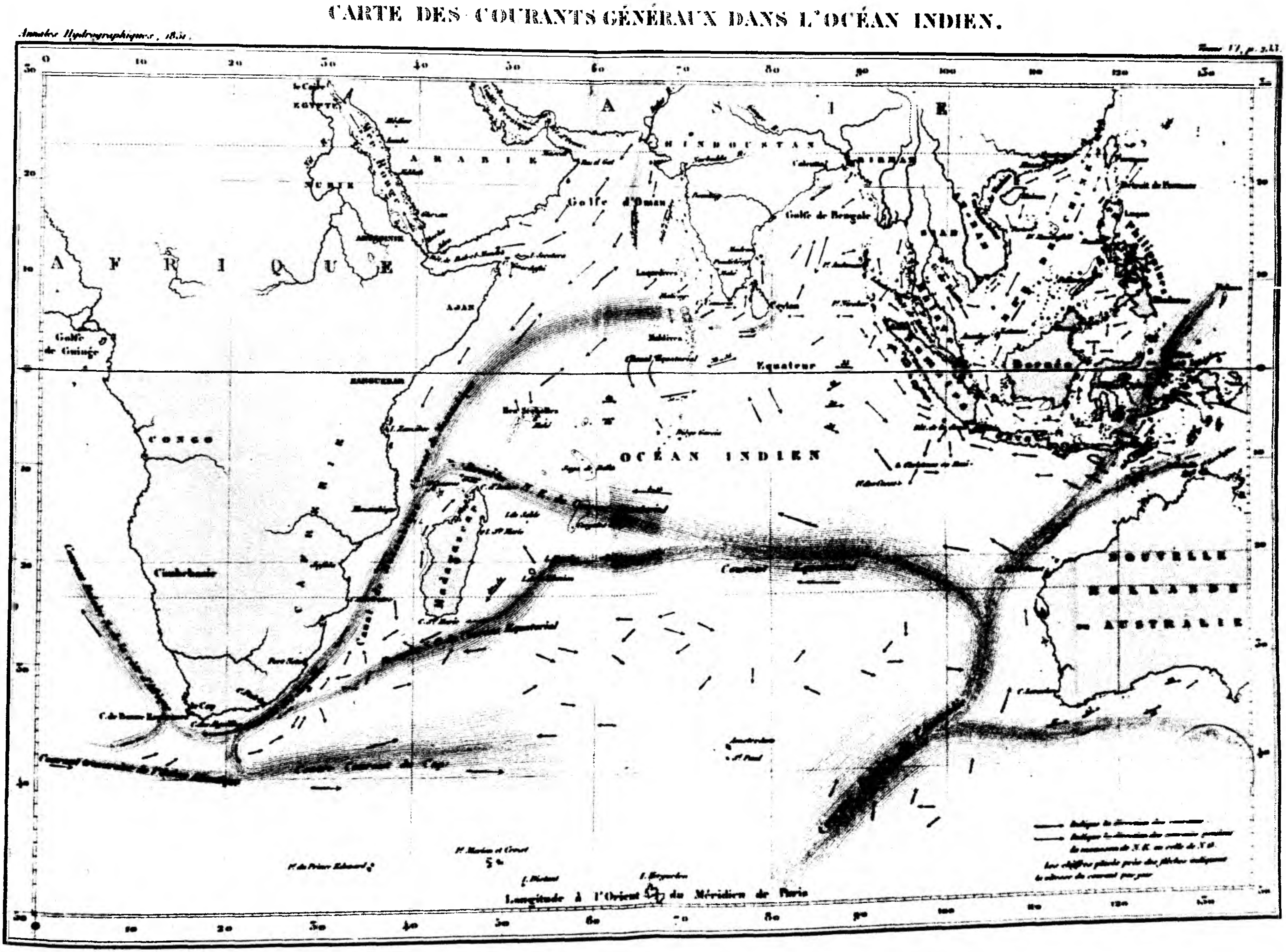


FIG.15(c). Chart of surface currents in the Indian Ocean by KERHALLET (1851a).

also made brief reference to Wilkes while discussing the Pacific. (Note that the pictorial style used for his three maps much more closely resembles that used by Wilkes than those used by Rennell and Berghaus.)

Kerhallet's Atlantic chart combines features in the middle and low latitudes from charts of the previous two decades, while making more conspicuous the flow of surface waters into the Mediterranean Sea. The portion of the North Equatorial Countercurrent depicted by Wilkes and a countercurrent south and east of the Gulf Stream included on maps beginning with Rennell's were retained by Kerhallet, as was Rennell's branch of the North Equatorial Current veering into the central Sargasso Sea. Kerhallet's significant improvements were in the high latitudes, which make his map of the Atlantic the best produced thus far. The southward East Greenland Current is now clearly shown to flow around the terminus and back north on the western side of the peninsula, which was implied with a set of arrows by Berghaus and not shown at all by Wilkes, and a northeastward branch of the Gulf Stream is shown to extend to the north of the British Isles. In the South Atlantic, Kerhallet reinstated the Agulhas Current retroflection, which had been dropped by Wilkes, and he retained Wilkes' portrayal of the confluence of the Brazil and Falkland currents while commenting in the text about the regional variability. A large improvement was made when Kerhallet showed a continuous eastward flow from Drake Passage to the area south of Africa, but stemming from a very meager data base he had the zonal flow in the middle of the basin shifting too far north.

For the Pacific Ocean, Kerhallet made citations to the earlier work and chart of Duperrey, as well as to Berghaus' additions and Wilkes' discussions of the North Equatorial Countercurrent. As in the Atlantic, Kerhallet combined on his Chart of the Pacific features shown on the charts by Berghaus and Wilkes, with the addition of a continuous zonal flow across the southern part of the basin. The non-existent current described by Duperrey and copied by Berghaus as coming directly from the unknown Antarctic region was removed, but drift vectors pointing nearly straight north were included as Wilkes had shown. Kerhallet was more cautious than Wilkes in dealing with the western tropical region, and like Berghaus he showed no North Equatorial Countercurrent there, but rather a monsoonal reversal. He did, however, extend the countercurrent farther east, almost to Central America. He also showed the Kuroshio Current as originating with the North Equatorial Current, as Berghaus had originally done, but he followed Wilkes' example in showing a branch of the Kuroshio as extending directly northeast to the Bering Strait.

The Indian Ocean map by Kerhallet is similarly much like those drawn by Berghaus and Wilkes, but unlike his other two charts Kerhallet did not draw a zonally continuous flow in the southern part of the basin, and thus the continuity of flow in the Southern Ocean was interrupted. Much like Wilkes had done, Kerhallet showed a branch coming from the Antarctic that split into two branches off southwestern Australia, the northern of which again split to provide water to the Pacific through the Indonesian Seas. The monsoon changes in the northwestern Indian Ocean were understood fairly well, but the seasonal changes of flow patterns in the east would require many more observations before they could be dealt with adequately.

3.7. Alexander George Findlay – global surface circulation

Following behind John Purdy in the preparation of sailing directions for the British Admiralty was A.G. Findlay (1812-1875). Findlay initially worked to enlarge and update the directories published under the supervision of Purdy, and in the year after Kerhallet completed his original essays for the three oceans (revisions followed), FINDLAY (1853) presented to the Royal Geographical Society his own descriptions of ocean currents, and a map to accompany them

(Fig.16).

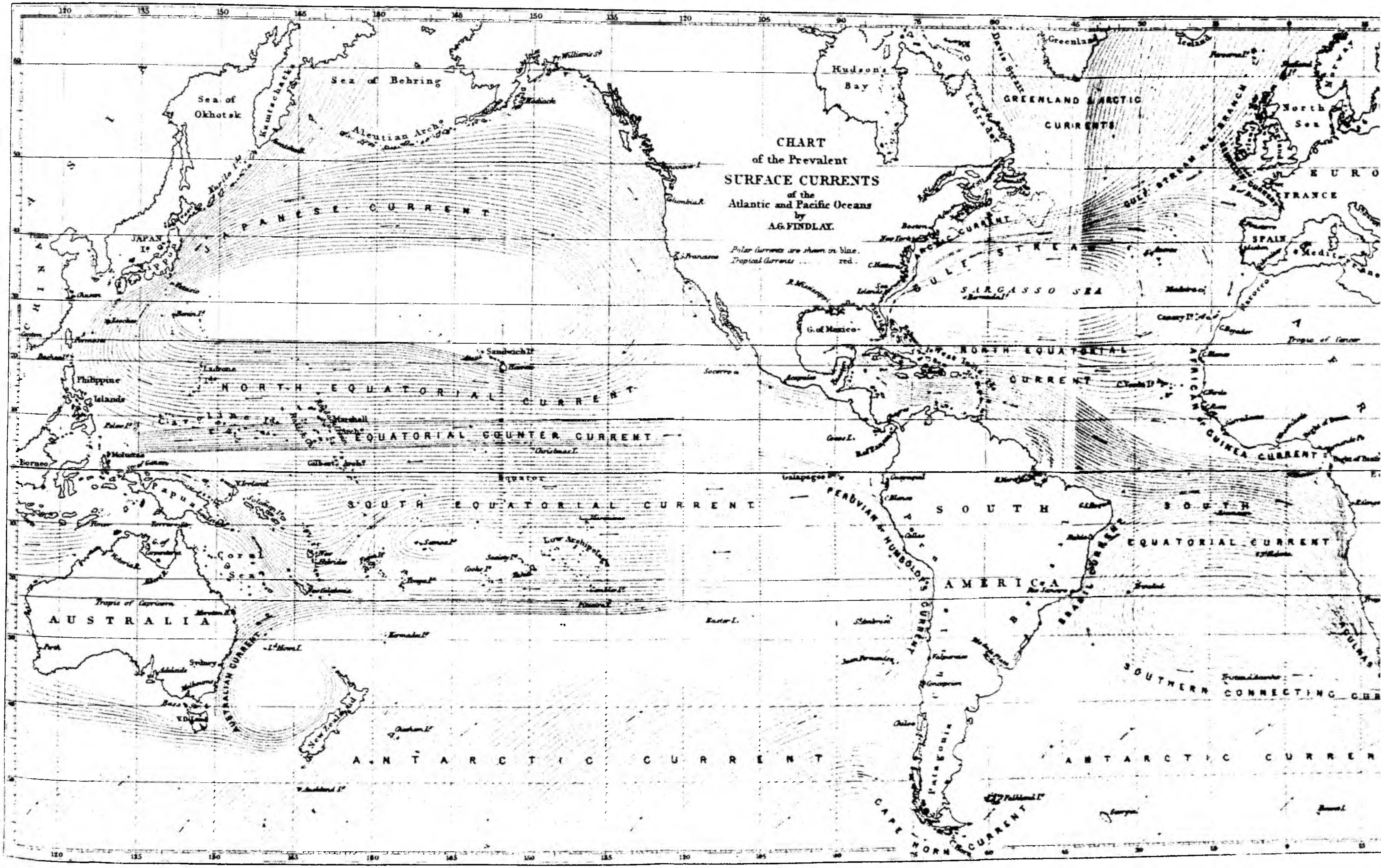
At the beginning of his text, Findlay observed, "While almost every department of geographical science has of late made great advances through the exploration of zealous inquirers, one branch, that of the circulation of the waters of the earth, has remained nearly stationary. Although detached facts and numerous observations have been recorded, yet the generalization of these data, and their reduction to a uniform system, remain nearly in the same state as when Major Rennell completed his 'Investigation of the Currents of the Atlantic'". This could hardly have been said in view of the great amounts of work done by Humboldt, Berghaus, Wilkes and Kerhallet, but yet, Findlay repeated these remarks over the remainder of his working career and three decades after he first made them they were still being published (e.g. Findlay, 1883); this sentiment can still be found in present-day literature.

Why Findlay should have maintained such a viewpoint is not particularly clear. In his works he made frequent citations to individual investigators from various nations, but only to the extent that their particular observations could be used to support his overall descriptions. This includes a modest number of citations to the atlas by Berghaus and the narrative by Wilkes. In his first paper, Findlay made no mention of Kerhallet, possibly because internal instabilities in France, resulting in the overthrow of the monarchy during 1848-1852, made it difficult to obtain French materials published then. But in later papers Findlay did refer to Kerhallet, and from one comment (Findlay, 1876) there might be gleaned certain feelings of nationalism and competition: "The work of Kerhallet, drawn up for the French Depot de la Marine, which has been in some degree adopted here, is thus based on previous English works, but the author claims for many of these directions a French origin, apparently with some justice".

In his first paper, Findlay sided with the conventional ideas about wind being the primary motive force and that the trade winds caused accumulations of water that resulted in pressure heads at the western sides of oceans. His comments about this were relatively brief, and he restricted his discussions of currents, and his map, to the Atlantic and Pacific oceans.

Findlay first described the currents in the Atlantic as they were known to Rennell, and then he updated the picture where he thought necessary. He discussed the Labrador Current as extending southward as far as Cape Hatteras and the probability of some of this cold water forming a submarine current beneath the Gulf Stream, features already described or depicted by Wilkes and Kerhallet. But certain other improvements made by Wilkes and/or Kerhallet, such as descriptions of the West Greenland Current, the Loop Current in the Gulf of Mexico, and the start of the North Equatorial Countercurrent, were not adopted by Findlay. Neither would he include a countercurrent south and east of the Gulf Stream, though he offered no justification for excluding it. This exclusion appears to have originated with Findlay, and it would soon become standard in subsequent works by other authors. The seaward return flow of the Gulf Stream was now becoming lost, not to be realized anew for many decades. Perhaps it was felt that such a feature could be safely sacrificed for the purpose of achieving smooth and symmetric patterns, especially since it certainly could not have been easy to detect at the surface owing to the prevailing winds (though it is now clear in dynamic height fields (Reid, 1994)). Findlay's rendition of the subtropical gyre was the most symmetric made yet, a subtle retreat from the quality of the portrayal made by Wilkes eight years earlier.

In the South Atlantic, Findlay presented a very noticeable convergence between the South Atlantic subtropical gyre and the Southern Ocean along about 40°S, essentially where Wilkes had placed it in the west and where we find it today. Another interesting aspect of Findlay's patterns is the lack of a retroflection of the Agulhas Current south of Africa; the Benguela Current was shown as being fed completely by the Agulhas Current whereas the southern limb of the South



Published for the Journal of the Royal Geographical Society by John Murray, Albemarle Street, London 1853

FIG. 16. Chart of surface currents in the Atlantic and Pacific oceans by FINDLAY (1853).

Atlantic subtropical gyre flows unimpeded into the Indian Ocean. He would, however, show an Agulhas retroflection in subsequent charts (e.g., FINDLAY, 1866 and later).

While introducing the Pacific Ocean, Findlay wrote: "In treating the currents of the Pacific, we enter upon a comparatively new subject – one upon which little has been written; and that little certainly not satisfactory, nor confirmed by more extended observations". He further claimed: "Two currents at least, of immense magnitude, and of the greatest importance in the future commerce of the Pacific, have not hitherto appeared on physical charts nor descriptions, and are placed for the first time on the chart before you". The two currents of which he spoke were the North Equatorial Countercurrent and the Kuroshio Current, both having been previously depicted and described by Berghaus, Wilkes and Kerhallet, though Findlay was the first to show the North Equatorial Countercurrent as extending all the way across the Pacific. As in the North Atlantic, Findlay showed the North Pacific subtropical gyre as being relatively symmetric, and in both the north and south his map shows a conspicuous poleward western boundary current. In his text, however, he moved away from the similarities noted by Wilkes and contended that while the warm currents in the western Atlantic were the most outstanding flows there, the eastern boundary currents held that distinction in the Pacific. He thought this because of the less constant trade winds in the Pacific and the greater width of the Pacific which would result in greater masses of water needing to be set into motion. Lastly, a rudimentary Alaska Gyre is shown, apparently the first explicit depiction of it.

3.8. Matthew Fontaine Maury – global circulation: surface, subsurface, theories

In the long history of ocean investigations, a uniquely contentious place is occupied by the name of M.F. Maury (1806-1873). His admiring biographers have enshrined him with titles such as "Pathfinder of the Seas" (LEWIS, 1927; WAYLAND, 1930) and "Scientist of the Sea" (WILLIAMS, 1963), while in various other ways he has been hailed as the "father" or "founder" of modern oceanography. But to many who have endeavored to critically read his scientific works, such high regard is questionable and often unacceptable.

Maury was born near Fredericksburg, Virginia of distinguished family lines. His family moved to frontier Tennessee when he was four, where he was raised in a strict religious environment before becoming a Navy midshipman in 1825. He was at sea for seven of the next eight years, mostly in the South Pacific, during which time he began work on a book entitled, *A New Theoretical and Practical Treatise on Navigation*. After returning from sea in 1834 he married his first cousin Ann Herndon in Fredericksburg, where they remained for the next seven years. He published his first scientific paper then, which was concerned largely with winds and air pressure near Cape Horn. The book was completed and published in 1836, and was soon adopted as the textbook for navigation by the newly-established Naval Academy at Annapolis. The book even gained the endorsement of Edgar Allan Poe, who at the time was a literary editor in Richmond. Soon thereafter Maury began writing under a pen name newspaper and magazine articles that were highly critical of the former Secretary of the Navy and of the navy itself. He also advanced a scheme to enhance southern commerce by having ships sail the great circle route to and from Europe, an idea soon taken advantage of by a British author (LEWIS, 1927). In late 1839 Maury suffered a broken leg when the stagecoach he was riding in overturned, and because the leg was improperly set his recovery was slow and painful; he would never regain the full use of his leg and thus never be reassigned to sea duty. While he was incapacitated from military service, he continued to write articles under his pen name, offering many suggestions for naval reform that were instituted by Congress. These were so well received by President Taylor that he wanted to make Maury his

Secretary of the Navy, even though Maury was just a lieutenant and still incapacitated. In 1842, the year that Wilkes returned from the United States Exploring Expedition (Section 3.5), Maury was recalled to active duty and appointed to Wilkes' old position – that of superintendent of the navy's Depot of Charts and Instruments. The Depot was renamed the Naval Observatory when it was moved to a new building in 1844. In the same year Maury published a paper about the Gulf Stream. He held this position for nineteen years, until the outbreak of the Civil War in 1861 when he resigned his commission to assist in the Confederate cause.

In his capacity as superintendent, Maury had access to logbooks from around the world, from which he extracted observations of the sea and weather. This work provided the basis for his *Wind and Current Charts*, first published in 1847, and his *Explanations and Sailing Directions to Accompany the Wind and Current Charts*, published in 1850 and later. These drew the attention of Alexander von Humboldt, who was working on his own manuscript on ocean currents (never to be published), and who suggested to Maury that he take the lead in getting standardized observations made at sea from vessels of all countries (KORTUM, 1990). Maury thus called for an international Maritime Conference, which was held in Brussels in 1853. The historic conference resulted in a form of logbook for warships, and another for merchant vessels willing to cooperate, for recording environmental information during both peace and war. This accomplishment is generally recognized as being one of Maury's greatest contributions. Having an accepted set of standards for making observations likely led to more observations being made, and it simplified the task of reducing them for analysis.

Maury's sailing directions proved to be of considerable value in shortening the times spent in sailing from one port to another, and thus in saving money for the operators of merchant vessels. One example is that in 1848 the typical sailing time from New York to Rio de Janeiro was 55 days, but Maury laid out a route that he predicted would reduce the time by 10-15 days, on which he was proven correct (LEWIS, 1927). He had similar success with other routes and hence he gained a considerable amount of fame. His celebrity status grew even further with his part in the Brussels conference.

In December of 1853 the Philadelphia firm of E.C. and J. Biddle was in the process of publishing an edition of Maury's sailing directions when company representatives conveyed to Maury, through his army-lieutenant nephew, their belief that Maury's knowledge of the sea and atmosphere would be of great interest to many others besides mariners and that he should prepare a book on the subject. They also pointed out that Maury's previous writings were not protected by copyright, so they warned him to write the book as rapidly as possible and secure a copyright or he would soon see "some Yankee bookmaker steal his thunder and reap a fortune from it". With this they touched Maury's southern sensitivities and his ambitions for wealth and greater fame. Humboldt had earlier used the term "Physical Geography of the Sea" for the growing field of marine physics (MAURY, 1855), and it was this term that was agreed upon as the title for the book (WILLIAMS, 1963).

The Physical Geography of the Sea was written, largely on the basis of his previously published works on the ocean and atmosphere, during off-duty hours in the spring of 1854. It was completed on June 20 and published by Harper & Brothers in New York in early 1855. It was an immediate success that warranted five printings in America in just the first year. It was also published the same year in London by Sampson Low, and was soon translated into various other languages. In America, the first revision and enlargement came out in 1856, followed by others in 1857, 1859, 1861 and 1871 (the eighth edition of 1861 represents the final form according to LEIGHLY (1963)). It has very often been referred to as the first textbook of oceanography. But this is not particularly appropriate in view of Isaac Newton's editing and use as a text of Varen's *Geographia Generalis*, first published in 1650 when the hydrospheric sciences were coming to be thought of as being branches of geography. Marsigli's book *Histoire physique de la Mer*, published in 1725, may also have been used as a textbook, as well as Rennell's book published in 1832, Berghaus' 1837 treatises on ocean circulation, and the 1845 narrative by Wilkes.

Maury's style of writing was an essential factor contributing to the commercial success of *Physical Geography of the Sea.* Coming from the background that he did, Maury deeply believed in the divine order of nature and that any seeming contradictions between the Bible and observations could be worked out with better vision. He attempted to do this in his book. Writing with an oratorical rhythm that appealed to the public, he referred frequently to the scriptures and laced his prose throughout with metaphors. For example, MAURY (1855) opened the first chapter of the book with: "There is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows. Its banks and its bottom are of cold water, while its current is warm. The Gulf of Mexico is its fountain, and its mouth is in the Arctic Seas. It is the Gulf Stream".

As much as the public admired Maury's work, scientists of the day objected to it, a dichotomy that has continued into our own century. In contrast with some of Maury's biographers and admirers who have variously referred to him as the "founder of modern oceanography", others have been more circumspect. LEIGHLY (1968) remarked that when interpreting observations Maury "brought a lively imagination and unlimited self-confidence, but only the most superficial knowledge of physical science. This combination of qualities led him into grandiose but often fantastic generalizations concerning the circulation of the atmosphere and the oceans, which were justly rejected by his scientific contemporaries". LEIGHLY (1963) has given several examples of criticism directed at *Physical Geography of the Sea* by Maury's contemporaries, and he has also observed that when writing articles under a pen name Maury "acquired the habit of hortatory and polemic utterance that remained with him throughout his life". These qualities of writing, and Maury's often ill-conceived explanations of natural phenomenon, were extensions not only of his personality but of his philosophy as well. In a letter to his friend Frank Minor in July 1855, Maury observed (LEWIS, 1927): "It's the talent of industry that makes a man. I don't think that so much depends upon intellect as is generally supposed; but *industry and steadiness of purpose*, they are the things."

The most acrimonious criticisms of Maury were directed at his explanations of atmospheric circulation. Among other misconceptions, he contended that low air pressure and rising motions exist over the poles (in spite of evidence to the contrary), that each particle of air brought into the surface convergence near the equator would rise and cross into the opposite hemisphere from which it came (his "crossing of the winds"), that Hadley's theory was inadequate to account for the trade winds (mistakenly attributed to Halley), and that the atmospheric circulation was controlled by Earth's magnetic field (because Faraday had detected a magnetic response in oxygen). There are other examples of Maury's impulsiveness in proposing theories about the atmosphere, and increasingly in later editions of the book they were accompanied by harsh attacks on opposing theories.

With respect to the oceanic circulation, Maury presented much that was correct, some of it new, but his discussions were often so shrouded in contradictory speculations that their value could not be very large in the eyes of his more scientific peers. Aside from the direct criticisms of his work, Maury enjoyed rather few supportive citations from his contemporaries, which indicate his views had relatively little influence. Similarly, Maury seldom cited the literature, except when specific observations or an occasional theory from another field could be used to promote his ideas. This is not to say, however, that Maury was not influenced by the oceanographic community, as it appears that he kept relatively well informed about what his peers were doing; making rational syntheses of the various concepts is what gave him trouble. Because Maury made few citations, particularly with respect to ocean theory, we can only make inferences about his sources. The most important ones seem to have been Humboldt and Wilkes. As we describe below, Maury took a strong, and for the era unusual, position in favor of there being a deep circulation driven by differences in density, an opinion that was probably impressed upon him by both Humboldt and Wilkes. Perhaps this area is where Maury's contributions were most germane, for in later editions of *Physical Geography of the Sea* he interpreted cold temperatures at depth, like Wilkes had done, as evidence of a deep thermohaline circulation. Maury was given due credit for this in 1870 when William Carpenter sided with the interpretation (Section 3.12). But unlike Humboldt and also unusual for the era, Maury discounted wind as being an important cause of ocean currents, saying instead that differences in salinity and temperature were in all cases the foremost causes. This opinion was similar to that of Wilkes. We do not know what kind of a personal relationship existed between Maury and Wilkes, but in view of Maury having returned to active duty the year Wilkes concluded his expedition and that Maury was appointed to Wilkes' previous job, it is quite likely that Maury gained much from Wilkes.

Because of Maury's elevated status in the history of oceanography it is necessary that we take a look at some of his specific writings. Here we draw from the original version of *Physical Geography of the Sea* (Sampson Low). The basic ideas set forth in it remained largely unchanged in subsequent editions, but as criticism to his theories mounted he added rebuttals while expanding his expositions. A short new chapter was dedicated to subsurface oceanic temperatures (see, for example, the eighth edition of 1861 reprinted by LEIGHLY (1963)), the subject of a new field that Maury called "the actinometry of the sea" (from actin, a Latin prefix relating to light). On the basis of some measurements showing warmer water a few meters beneath the surface, and on the rationale that evaporation continuously cools the surface faster than it is heated by solar radiation, he proposed a general hypothesis that the greatest temperatures must lie at some depth beneath the surface. Though this has not been substantiated, he was able to describe what we now think of as vertical turbulent mixing of properties caused by surface waves, and he seems to have been original in his thinking about it.

MAURY (1855) began his discussions of ocean circulation with the Gulf Stream and with what was thought to cause it. The prevailing opinion since before the time of Franklin was that the trade winds in the tropical North Atlantic were responsible for a pressure head in the Gulf of Mexico, downhill from which ran the Gulf Stream (as we have noted earlier, this idea was accepted as being the most plausible until the 1940s (i.e., SVERDRUP, JOHNSON and FLEMING, 1942)). Maury assailed the pressure-head concept on several points, three of them being: if the Gulf Stream were indeed running down from an elevation it should spread out into the Atlantic instead of remaining narrow; because of the comparative widths and speeds of the Gulf Stream off Bimini and Hatteras the current becomes nearly fifty percent shallower downstream and thus the waters at its base are running uphill; the cold Labrador Current from the north is correspondingly strong and yet there is no system of winds that can produce a similar pressure head in Baffin's Bay to drive it. Maury then invoked the argument, as Wilkes had, that the drifts of icebergs demonstrated there being an extension of the Labrador Current flowing south beneath the Gulf Stream, and because a submarine current so far removed from its source could not be propelled by winds there must be some other cause. Maury took this to mean that "winds have little to do with the general system of aqueous circulation in the ocean". After observing that Earth's rotation imparts a much greater eastward speed to southern Gulf Stream waters than to those off the Grand Banks, he surmised there must be a retarding force toward the west much greater in magnitude than the westward force of the trade winds, a conclusive reason in his opinion for discarding the importance of wind.

As an alternative theory for what causes the Gulf Stream, and for why it remains narrow, Maury cited naval research showing copper-clad ships to corrode more rapidly in the Gulf Stream than in the open Atlantic, and this suggested to him that the waters of the Gulf Stream have "chemical affinities peculiar to themselves, but, having more salts, they are therefore specifically heavier than the sea water through which they flow in such a clear and well-defined channel. The affinities of which I speak, and which are manifested in the reluctance of the Gulf Stream to mingle its waters with those of the ocean may be the resultant of their galvanic (chemical) properties, higher temperature, and greater degree of saltness, all combined. If the story told by the copper be taken to mean a higher point of saturation with salts, and, consequently, a greater specific gravity of the waters of the Gulf Stream and Caribbean Sea than for the waters of the broad ocean at the same temperature, then we should have as a source for the initial velocity of the Gulf Stream, not, indeed, a higher level of the waters in the Gulf, but a greater density. Now a greater density, implying, of course, a greater specific gravity, would serve, as well as a higher level, to impart an initial velocity, but with this difference: the heavier waters would, by reason of their pressure, be ejected through the most convenient aperture out into the ocean of lighter waters by sort of a *squirting* force."

On the one hand, Maury acknowledged the elevated temperature of the Gulf Stream, but on the other he maintained that the greater salinities of Gulf Stream waters cause them to be denser than surrounding waters at the same temperature. Although he used this confused logic to conclude that the Gulf Stream is propelled by density-induced pressure, he would observe not much later that "Water, we know, expands by heat, and here the difference of temperature may more than compensate for the difference of saltness, and leave, therefore, the waters of the Gulf Stream lighter by reason of their warmth". He further described the core of the Gulf Stream as standing higher than adjacent waters, his "roof-shaped" Gulf Stream.

To illustrate how the Gulf Stream could be a result of high temperatures, Maury presented an analogy in which the upper stratum of the tropics was oil, and because of its low density it would spread poleward, turn to water and sink, and then return toward the equator at depth before rising and turning back to oil. This was no doubt inspired by Rumford's meridional circulation scheme (Section 2.5.5). Maury extended the argument a step further and considered the deflecting effect of Earth's rotation on meridional flow, as Hadley had done for the trade winds. Maury described the poleward oceanic flow at the surface as being deflected toward the east, and the deep equatorward flow toward the west. This implies eastward surface flow in the tropics as opposed to the actual westward flow, and it stands in contradiction to the Gulf Stream originating from tropical flow although Maury nonetheless used it as an explanation for the Gulf Stream. Only in later editions would Maury address the contradiction, saying it was caused by unknown reasons. Maury also recognized the great climatic importance of the particular discovery that led Rumford to the convective scheme – that, unlike freshwater, sea-water does not reach maximum density at some temperature above the freezing point. Wilkes was unaware of this when he interpreted deep-sea measurements of approximately 4°C from unprotected thermometers as indicating a homogenization at maximum density (Section 3.12), so it seems likely that Maury gained this insight, and the appreciation for the effects of Earth's rotation, from his associations with Humboldt.

Maury occasionally conceded in the book that wind can propel the sea surface, but he maintained that such effects were local and temporary. To further promote the importance of density he cited additional evidence for the existence of submarine currents. The most vivid example was attributed to Lieutenants Walsh and Lee, who "made some interesting experiments on the subject. A block of wood was loaded to sinking, and, by means of a fishing line or a bit of twine, let down to the depth of one hundred or five hundred fathoms (six hundred or three thousand feet) (200 and 1000m). A small float, just sufficient to keep the block from sinking farther, was then tied to the line, and the whole let go from the boat. To use their own expressions, 'It was wonderful, indeed, to see this *barrega* move off, against wind, and sea, and surface current, at the rate of over one knot an hour (0.5m.s^{-1}), as was generally the case, and on one occasion as much as 1¾ knots (0.9m.s^{-1}). The men in the boat could not repress exclamations of surprise, for it really appeared as if some monster of the deep had hold of the weight below, and was walking off with it'". Maury did not say where these observations were made, though FINDLAY (1853) mentioned they were made in the southern Sargasso Sea. According to the eighth edition of *Physical Geography of the Sea* (LEIGHLY, 1963) the source material lies in Maury's *Sailing Directions* of 1851, to which we have not had access.

Maury's conviction in the paramount importance of density was so strong that he declared: "... we may lay it down as a rule that all the currents of the ocean owe their origin to difference of specific gravity between sea water at one place and sea water at another; for wherever there is such a difference, whether it be owing to difference of temperature or to difference of saltness, etc., it is a difference that disturbs equilibrium, and currents are the consequence. The heavier water goes toward the lighter, and the light whence the heavier the comes; for two fluids differing in specific gravity, and standing at the same level, can not balance each other". He went on to describe ice-free areas in the Arctic Ocean as being the result of undercurrents bringing in relatively warm water that rises to the surface.

The existence of salt in the ocean was to Maury the fundamental reason for there being currents, because if the ocean were fresh the temperature of maximum density (~4°C) would restrict vertical convection and thus the horizontal currents set up by it. But because there is salt, and because evaporation and precipitation lead to spatial variations in salinity, the resulting differences in density would necessarily lead to a system of currents working to restore equilibrium. After echoing Rumford about the importance of ocean circulation in climate, Maury posed the question: "Here, then, is an office which the sea performs in the economy of the universe by virtue of its saltness, and which it could not perform were its waters altogether fresh. And thus philosophers have a clew placed in their hands which will probably guide them to one of the many hidden reasons that are embraced in the true answer to the question, 'Why is the sea salt?'"

In a similar vein, Maury viewed the existence of sea shells as facilitating a divine design for oceanic circulation: "The sea-breeze plays upon the surface; it converts only fresh water into vapor, and leaves the solid matter behind. The surface water thus becomes specifically heavier, and sinks. On the other hand, the little marine architect below, as he works upon his coral edifice at the bottom, abstracts from the water there a portion of its solid contents; it therefore becomes specifically lighter, and up it goes, ascending to the top with increased velocity, to take the place of the descending column, which, by the action of the winds, has been sent down loaded with fresh food and materials for the busy little mason in the depths below. Seeing, then, that the inhabitants of the sea, with their powers of secretion, are competent to exercise at least some degree of influence in disturbing equilibrium, are not these creatures entitled to be regarded as agents which have their offices to perform in the system of oceanic circulation, and do they not belong to its physical geography? ... Thus God speaks through sea-shells to the ocean".

The final chapter of the original version concerns the "drift of the sea". Maury applied this term to what he considered to be movements of the surface waters too slight to be detected with navigation but which must exist because of the temperature differences between high and low latitudes. In light of his previous statements about the importance of temperature and the density characteristics of sea-water in setting up a thermohaline circulation, it seems rather curious that in this chapter he made no mention of any vertical motion or deep currents; he discussed only the movements and exchanges or surface waters strictly on the basis of temperature. As reference for

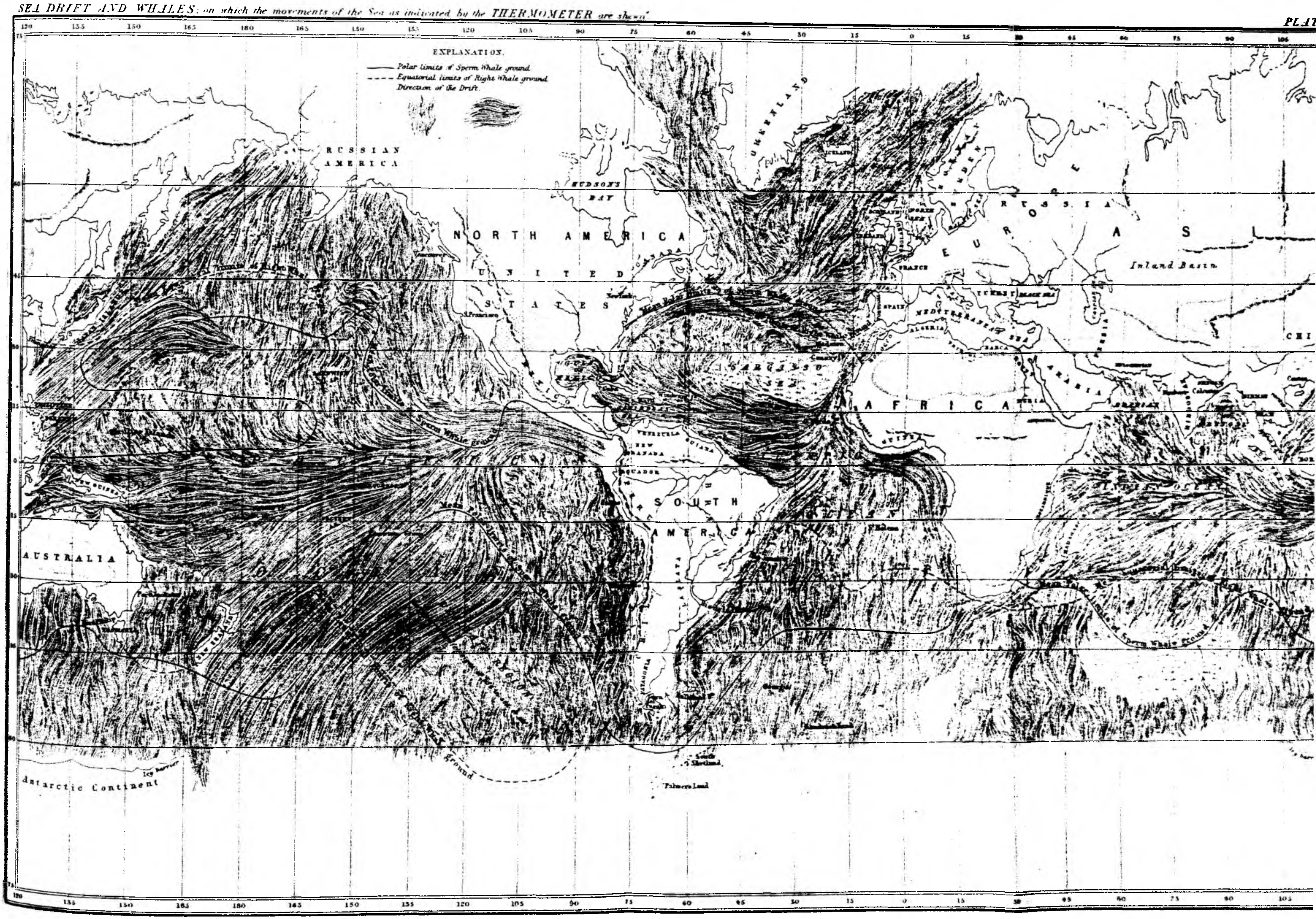


FIG.17. World chart of surface currents reproduced from *The Physical Geography of the Sea* (MAURY, 1855).

the reader, he presented a map of the global circulation (Fig.17), which contains information about whaling grounds in a manner following Wilkes. In Maury's words, "The object of Plate IX, therefore, is to illustrate, as far as the present state of my researches enables me to do, the circulation of the ocean, as influenced by heat and cold, and to indicate the routes by which the overheated waters of the torrid zone escape to cooler regions, on one hand, and on the other, the great channel ways through which the same waters, after having been deprived of this heat in the extra-tropical or polar regions, return again toward the equator; it is assumed that the drift or flow is from the poles when the temperature of the surface water is below, and from the equatorial regions when it is above that due the latitude. Therefore, in a mere diagram, as this plate is, the numerous eddies and local currents which are found at sea are disregarded. ... In overhauling the log-books for data for this chart, I have followed vessels with the water thermometer to and fro across the seas, and taken the registrations of it exclusively for my guide, without regard for the reported set of the currents". Other wording in the text indicates that Maury used no actual latitudinal averages of temperature but instead relied on subjective judgements as to whether a particular reading came from relatively warm or cold water.

Maury's method provided results consistent with previous studies chiefly in regions having important boundary currents, where anomalous temperatures for specific latitudes are the most obvious. But there are conspicuous exceptions. The East Australia Current appears as a northward flow, whereas the Benguela Current is shown as flowing toward the south. The latter is unexpected, in view of it being a relatively cold current and that the even colder upwelled waters adjacent to the southwestern coast of Africa had been earlier assumed by other authors to be of Antarctic origin. Sir James Clark ROSS (1847) had clearly described his encounter with the Benguela Current: "All these circumstances combine to show that a northerly current of very limited extent, but of considerable force, exists from the Cape of Good Hope, along the western coast of Africa; ... It is sufficiently well defined to afford useful notice to seamen of their approach to the land". Furthermore, Maury merged his southward flow in the Benguela region with the southward flow of the Agulhas Current to produce a band of water feeding directly south into the Southern Ocean. Though the Agulhas Retroflection was by then well recognized, there is no hint of it on the map. His rationale seems to have been based mainly on temperature readings from a single cruise showing water as warm as 23°C near 39°S; 10-15°E (based on the description of the cruise track), which is an area frequented by eddies of warm Agulhas water. His conclusion was: "Here, therefore, was a stream – a mighty 'river in the ocean' ... This is truly a Gulf Stream contrast. What an immense escape of heat from the Indian Ocean, and what an influx of warm water into the frozen regions of the south!" Another unexpected depiction was a southward extension of the Brazil Current to the Falkland Islands. In spite of mounting evidence to the contrary, Maury contended this had to be the case because of the noticeably warmer climate around the Falklands than that at South Georgia, which has a similar latitude.

The oceanic interior is where Maury's depictions most consistently differed from what had been learned from analyses of ship drift. The North Atlantic, having been so extensively surveyed, was the only major basin to receive a clearly depicted subtropical gyral circulation (the Sargasso Sea was for some unknown reason described and placed in the eastern basin). A hint of a gyre was drawn in the North Pacific, but this suffered because of the way the Equatorial Current system was drawn. To Maury, the North Equatorial Countercurrent was just another irregularity in a broad region of the Pacific where localized currents and countercurrents were to be expected. Here, the Equatorial Current system consisted of only a northern hemisphere branch in the east before being brought south of the equator in a widely-spreading plume. A portion of that was allowed to pass south of New Guinea and Borneo before it was turned north into the Kuroshio Current (which was not extended east to the California Current). In the text Maury considered there to be a need for the warm water of the Indian Ocean to escape into both the Atlantic and the Pacific, and in drawing parallels with the Gulf Stream he described the source of the Kuroshio Current as being in the Indian Ocean: "Between the physical features of this current and the Gulf Stream of the Atlantic there are several points of resemblance. Sumatra and Malacca (Malaysia) correspond to Florida and Cuba; Borneo to the Bahamas, with the old Providence Channel to the south, and the Florida Pass to the west." He depicted a flow as passing completely from the Pacific into the Indian Ocean north of Australia, the Indonesian Throughflow in present terminology, but he made no mention of it, perhaps because it conflicted with his statements about a general need for an escape of warm water from the Indian Ocean. Maury showed no gyral circulations anywhere in the southern hemisphere, nor any convergences between subtropical and subantarctic waters as had been demonstrated before him. He instead had alternating regions of northward and southward flow throughout the southern hemisphere that were intended to illustrate his theories of aequeous equilibrium.

It is evident that while Maury was a successful popularizer of science he personally lacked the objectivity and disciplined thought necessary for science. However, non-scientists have continued into our own century to further elevate his name as a scientist. For example, LEWIS (1927) wrote in a biography: "Maury's investigations of the winds and currents of the sea led him into researches connected with all the phenomena of the ocean, the results of which were so extensive and so valuable as to win for him the right to be called the first great oceanographer of the world". Such sentiment, though well-intentioned, is misplaced. Although Maury held some uncommon opinions about the ocean that were later verified, few were of his own creation, whereas most of those that originated with him were dismissed. He provided relatively little for the direct advancement of physical oceanography, with his cavalier attitudes and propensity for speculation being reminiscent of similar qualities surrounding the work of Kircher nearly two centuries earlier (Section 2.4.3). Indirectly, however, Maury's writings were highly beneficial in the sense that they helped to engender debate. Most notable were Maury's unacceptable descriptions of atmospheric motion that roused William Ferrel into quantifying the effects of Earth's rotation on relative motion in any direction.

3.9. William Ferrel – Earth rotation, the deflecting force, geostrophic flow

Maury's physical explanations were immediately assailed by William Ferrel (1817-1891), an instructor in Tennessee who was familiar with the LAPLACE (1778) tidal equations and who realized that the full effect of Earth's rotation contained in those equations could be applied to the general circulations of the atmosphere and ocean. Although the analysis by CORIOLIS (1835; 1836) came earlier, it was a treatment of relative accelerations over a planar surface as pertaining to problems of hydraulic machinery (BURSTYN, 1966b). It was not extended to motions over a rotating curved surface and its applicability to the motions of Earth's fluids was not realized (e.g., JORDAN, 1966). In studying the motions of projectiles relative to a rotating Earth, POISSON (1837) used an absolute coordinate system fixed in space to show that a body given an initial motion parallel to latitude lines would be deflected to the right of the initial motion just as if the initial motion were meridional (he made no distinction with regards to hemisphere in the translation given by ABBE (1910), but presumably he was thinking of only the northern). The applicability of this to fluid flow over the Earth was also not realized. To explain the rotary motions of atmospheric storms, TRACY (1843) argued heuristically that winds in any initial direction are deflected toward the right in the northern hemisphere and to the left in the southern. But Tracy's rationale lacked the need for Earth rotation when he contended "that a direct course, due east at the commencement follows a great circle and parting from the parallel reaches a lower latitude". The real physics of the problem concerning the atmosphere and ocean were still not understood.

In the first of a series of articles, FERREL (1856) refuted Maury's scheme of just two meridional atmospheric circulation cells in each the northern and southern hemispheres and the associated low pressures and rising motions over the poles. Ferrel cited observations indicating high pressures and thus descending motions over the poles, together with descriptions by Professor Espy about low pressures near the Arctic and Antarctic circles, to argue for the existence of three meridional cells in each hemisphere. (Espy apparently thought that the rains and snows in the low-pressure belts were the cause of the low pressures, but Ferrel pointed out that the reverse is instead true.) Ferrel further explained the three meridional cells as being the combined result of temperature differences between the high and low latitudes, conservation of total angular momentum (assumed to be zero) of the atmosphere about Earth's axis of rotation, and the effects of Earth's rotation on zonal as well as meridional flow. For eastward flow, he said, there would be an equatorward deflection, and for westward flow it would be poleward. He was the first to point out that the deflecting forces resulting from the Earth's rotation as contained in the Laplace tidal equations are applicable to large-scale relative motions. The discussion in this paper was mainly qualitative, but he did show parts of the tidal equations for the deflecting forces on meridional and zonal flows as (written in Ferrel's notation):

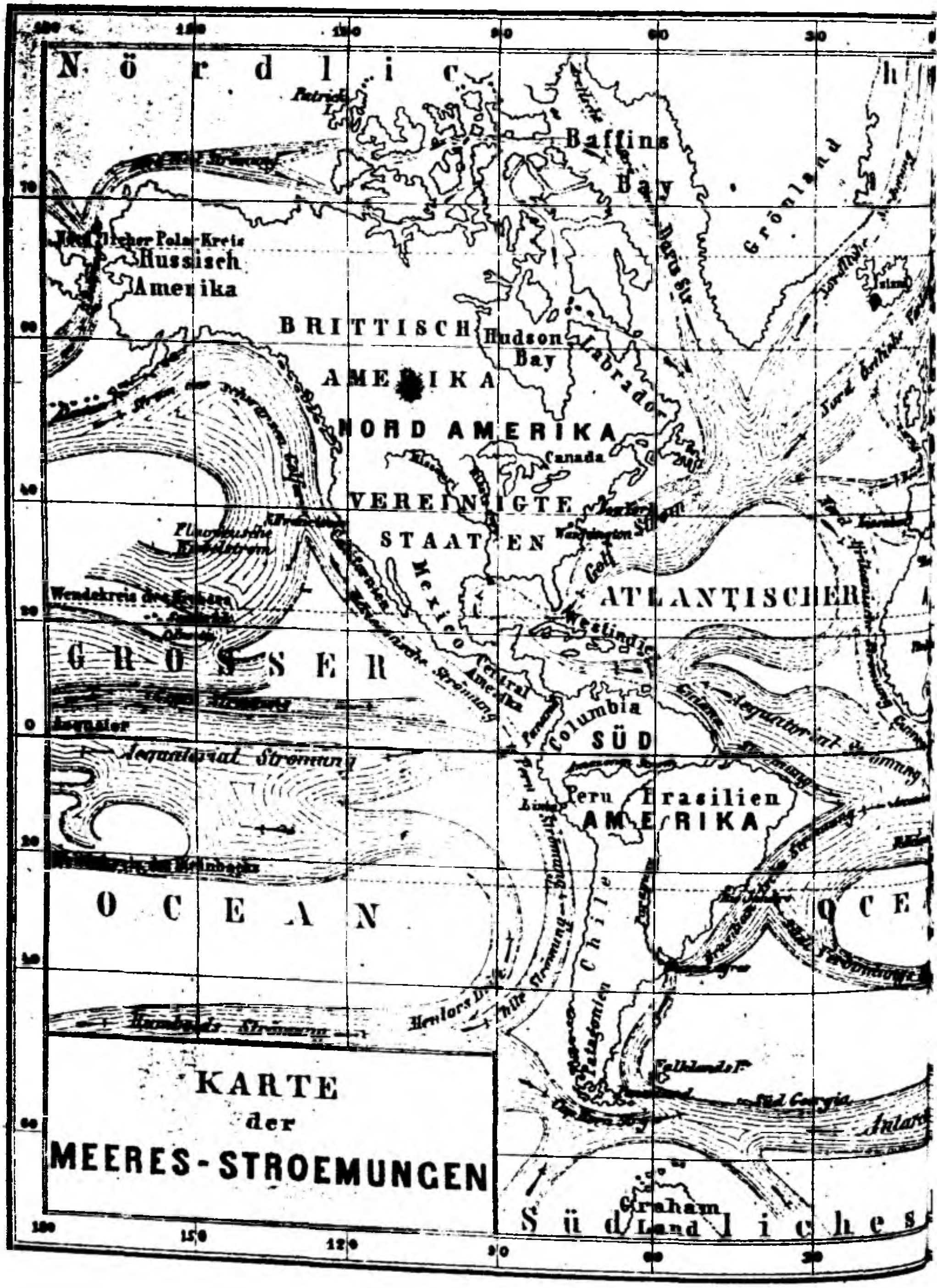
$$2\,n\,u\,r\,\sin l\,\cos l,$$

and

$$2\,n\,v\,r\,\sin l,$$

where n is the motion of the Earth at the equator, u and v are the northward and eastward fluid velocities, r is the radius of Earth, and l is latitude.

Ferrel thought "the *primum mobile* of the motions of the ocean, as of the atmosphere, depends principally upon the difference of temperature between the equatorial and polar regions". By using a coefficient for the thermal expansion of water and approximate vertical profiles of temperature in the low and high latitudes, he calculated that the surface of the equatorial ocean should stand three meters above that near the poles. Such would be the case if there were no meridional pressure gradients along the sea floor, and such a geometry of the sea surface would cause poleward upper-level flow, which in turn would create higher bottom pressures near the poles that would drive equatorward bottom currents and a hemispheric overturning cell, much like Rumford had proposed before the beginning of the century. "But this motion, combined with the rotatory motion of the earth, gives rise to other forces, just as in the case of the atmosphere, which greatly modify these motions". Here Ferrel departed from what Maury had proposed, and after disputing the importance Maury had placed on differences in salinity, Ferrel wrote that for the same reasons the atmosphere accumulates near the parallels of 28°, so should the oceans. But he was apparently not completely comfortable with this explanation, saying that "whatever may be the causes of the motions of the ocean," there is westward flow in the tropics and eastward flow near the poles, and because of the deflecting force on zonal currents there would be convergent components toward the centers of subtropical gyres. To maintain such zonal circulation at the surface and for it to be in balance with the deflecting force, Ferrel thought there would have to be an elevation of the sea surface near 28° latitude some twelve meters above that near the poles and nearly two meters above that near the equator. With his temperature profiles this would cause bottom pressure gradients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NORD AMERIKA
Canada
VEREINIGTE STAATEN
New York
Washington
Golf Strom
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Graham Land
Südliches
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Humboldts Strömung
Chile Strömung
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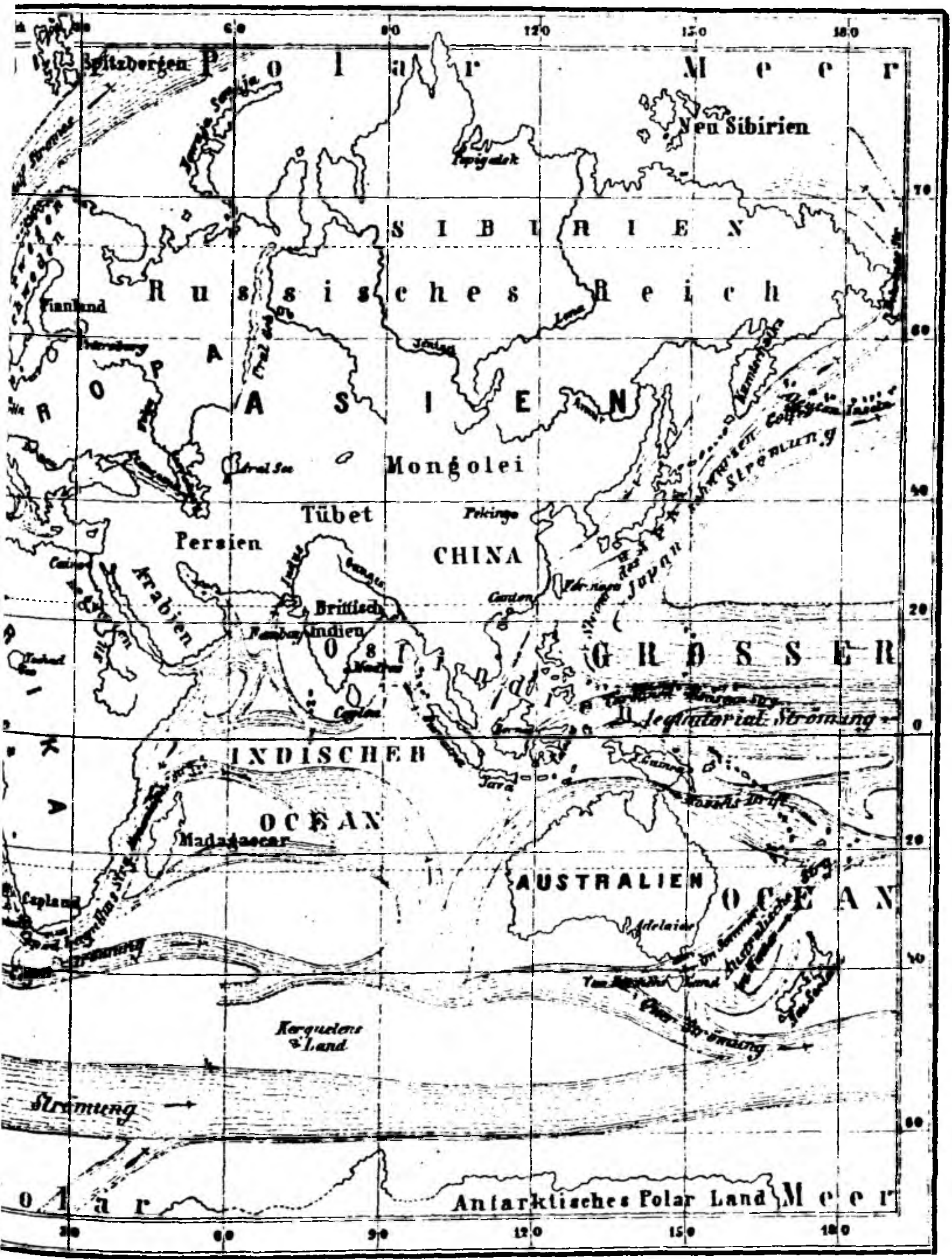


Zeichnung u. Lith. v. R. Linder. Berlin.

FIG. 18. World chart of surface currents by ZIMMERMANN (1865).

that would set up a two-cell overturning system associated with each subtropical gyre; the sinking would be centered at the accumulations near 28° latitude and the resulting variations in sea level would be half the initial variations. He used as supporting evidence "well-known" flow running poleward beneath the Labrador Current, the general equatorward drift of icebergs, and the accumulation of seaweed in the middle of subtropical gyres.

Misconceptions about the deep circulation aside, about which there was little information, the critical deficiency with Ferrel's explanation was that he did not invoke a continuous force that would maintain the flow. He was unable to do it with thermal driving, and because he wanted to see the same mechanisms at work in both the atmosphere and ocean he excluded any serious considerations of wind forcing. As EKMAN (1905) pointed out, the mistake was to consider ocean currents as free flows that continue to move by their own inertia after the moving force has ceased. But Ferrel was on the right track when he described deflections toward the interiors of subtropical gyres as producing higher elevations and that the deflecting force and pressure gradients would come to a balance. *The now-indispensable concept of geostrophic (Earth-turned) flow – where horizontal pressure gradients are balanced by the deflecting force to produce steady flow perpendicular to each – was thus comprehended.*

Concerning the intensity of the Gulf Stream, Ferrel offered an explanation where he qualitatively subtracted from water near the western boundary the deflecting force that would normally act on eastward flow – since there was no eastward flow, the southward impetus was nonexistent and thus a flow toward the north had to be the result. This argument was dropped in subsequent papers, but he continued to contend that the northward flow was strengthened by a pressure head produced in the Gulf of Mexico by westward tropical currents, which he thought would exist without the wind, and by a pressure deficit where the Gulf Stream turns off-shore. Although Ferrel introduced the concept of geostrophic flow, he did not realize the extent to which it obtains. As noted before, the pressure-head theory would remain the most durable of all theories regarding the Gulf Stream until the late 1940s and the realization of how latitudinal variations in the effect of Earth's rotation leads to westward intensification.

Ferrel's original paper was published obscurely, but in pamphlet form it was distributed by the Smithsonian Institution and personally by Ferrel himself to various scientists, libraries, and scientific associations in the United States and Europe. FERREL (1858-60) then provided a series of intricate analytical analyses for his theories of the atmosphere, which provided a basis for much productive work to follow. In 1859 he showed mathematically that the large-scale motions of the atmosphere are approximately hydrostatic and geostrophic, though he did not use the word geostrophic and he did not derive the simple expression we use today for geostrophic balance. But in more general terms than he used in 1856 he showed that "*in whatever direction a body moves on the surface of the earth, there is a force arising from the earth's rotation, which deflects it to the right in the northern hemisphere, but to the left in the southern.* ... This is an extension of the principle upon which the theory of the trade winds is based, and which has been heretofore supposed to be true only of bodies moving in the direction of the meridian" (FERREL, 1860). In an article written for a wide audience, FERREL (1861) summarized his analytical work and reiterated: "If v is the velocity of a body moving in any direction whatever, and F the deflecting force perpendicular to this direction, by resolving the forces and velocities in the direction of v and the perpendicular to it on the right we get:

$$F = 2\,n\,v \cos\theta$$

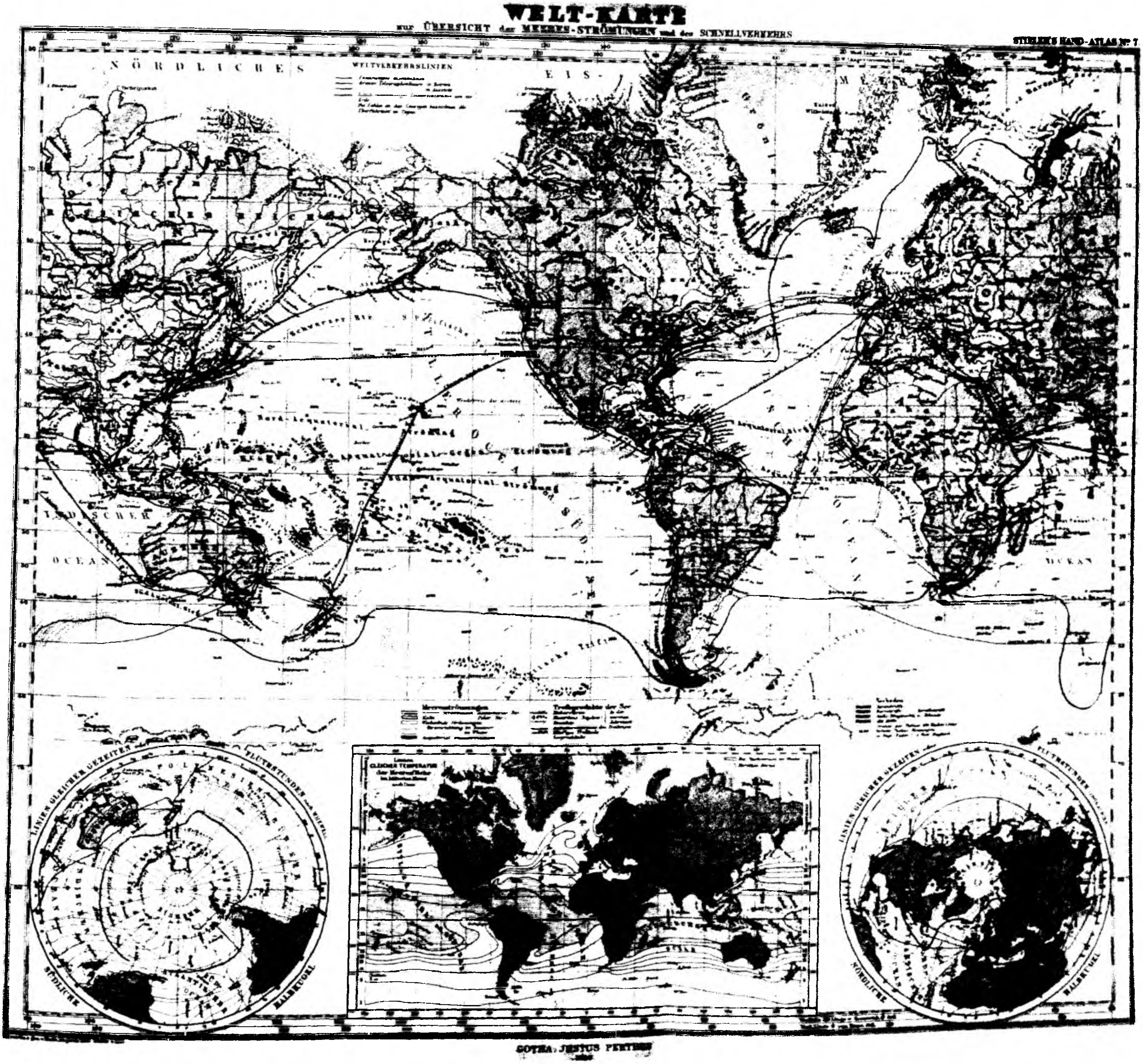


FIG.19. An 1867 version of Hermann Bergbaus' world chart of ocean currents reproduced from STIELER (1880).

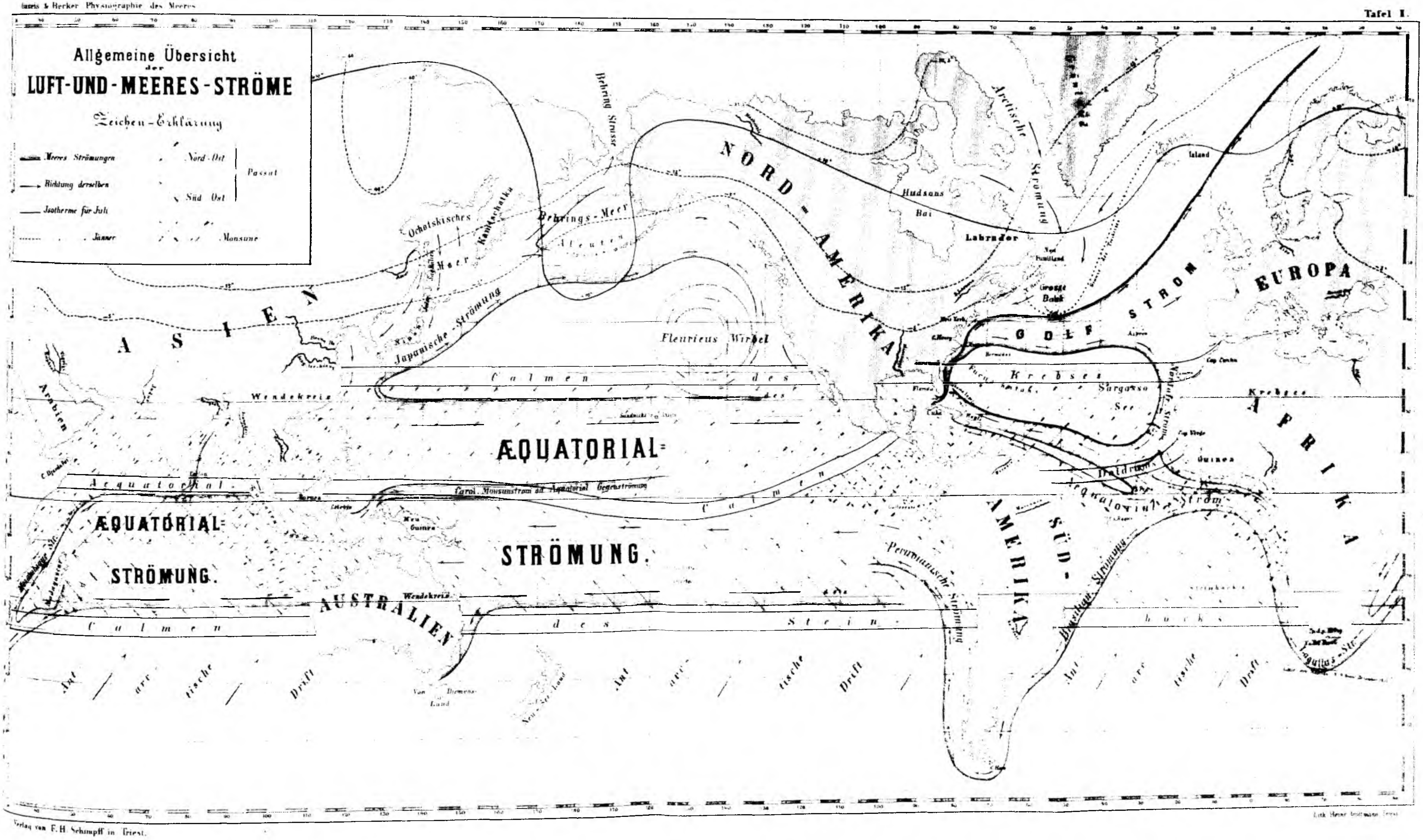


FIG.20. World chart of surface currents reproduced from *Physiographie des Meeres* (GAREIS and BECKER, 1867).

(n is the angular velocity of Earth's rotation is and θ is co-latitude). In the northern hemisphere, $\cos\theta$ is positive, but in the southern, negative. Hence, we have established this important principle, *in whatever direction a body moves, it is always deflected to the right in the northern hemisphere, and to the contrary in the southern hemisphere*". This simple, yet enormously important expression (now usually written as $F=2\Omega\sin\phi u$, where Ω is Ferrel's n, ϕ is latitude, and u is speed) was derived from the Laplace tidal equations independent of the analysis made by Coriolis for relative accelerations over a plane and of the investigations by Poisson of the motions of projectiles, though this force is now universally called the Coriolis force. Since CORIOLIS (1835) did not consider motion over a spherical surface he did not include latitudinal dependence and he did not write the complete expression we now call the Coriolis force. In a short history of ideas about the effects of Earth rotation on winds, LANDSBERG (1966) found no meteorological citations made to Coriolis prior to 1877 and concluded that "his contribution to the advancement of meteorology was nil", but that "the term *Coriolis force* has now become too ingrained into meteorological habits to suggest a change".

In the series of papers begun in 1858, Ferrel made frequent citations to contemporary scientists, but none to Maury (who had not incorporated any of Ferrel's ideas into revised editions of *Physical Geography of the Sea*). In connection with the ocean, Ferrel's discussions remained conceptual and were not much improved upon. He did come to accept the prospect of surface winds driving ocean currents, though to what extent in comparison with forces caused by density differences he was unable to say. Ferrel's contribution to oceanography was nonetheless outstanding because within two decades others would more fully work out the dynamical balances for the atmosphere and these in turn would be applied to the ocean (Section 3.14).

3.10. Hermann Berghaus; W.F.A. Zimmermann – global surface circulation

In one of his later works, MAURY (1864) included a map showing icebergs from the north drifting as far south as Morocco and Senegal. This, among other flaws, was harshly criticized by the physical geographer and publisher August PETERMANN (1865), who felt that the best pictorial display of ocean currents then available was a world map recently produced by the cartographer Hermann Berghaus (1828-1890), Heinrich's nephew. This map (BERGHAUS, 1863) was printed in color and on two sheets, each measuring 75 x 90cm. Water was colored light blue while the currents were depicted as thin white lines. Combined with its size, the color scheme of the map prevents us from reproducing it here. However, relatively little new information was presented and we are unaware of any text explaining the map. It appears that the Atlantic and Pacific portions were patterned after the first map by Findlay while other features shown earlier by Wilkes were also included (such as a well-defined loop current in the Gulf of Mexico and flows through the Bering Strait and the Indonesian Seas). The Indian Ocean was apparently patterned after the map by Kerhallet, with the main alteration being a continuity of flow along the southern limb of the south Indian subtropical gyre - the first such depiction we have seen.

Another map patterned mainly on previous work was produced by the German geographer W.F.A. Zimmermann (1797-1864), published in the year following his death (Fig. 18). ZIMMERMANN (1865) wrote for a general audience about Earth magnetism, the oceans, seas, rivers, glaciers and springs. It is unlikely that he conducted any original marine research, and because of the nature of the book he made few citations. His descriptions were not complete, and not always consistent with his map. For example, he described the Brazil Current as continuing south all the way to Cape Horn before turning west and then north along the west coast of South America, a possibility discussed by RENNELL (1832). But on the map there is no such westward turn around Cape Horn. The chart appears to have been patterned mainly after Kerhallet's maps, though Zimmermann mentioned Heinrich Berghaus and A.K. Johnston. The major departure from earlier charts is a continuous eastward flow in the Southern Ocean, which Zimmermann labelled as the Antarctic Current. This is the earliest depiction of the circumpolar current we are aware of, but in the text Zimmermann made no mention of it, nor of the circulation in the Weddell Sea. ROSS (1847) described an eastward current near Kerguelen Island in the Indian Ocean, and it could be that Zimmermann had heard of similar drifts observed elsewhere in the open Southern Ocean. But the lack of a pertinent description makes this seem unlikely, especially in light of the sparse data base for the Southern Ocean and the prevailing beliefs among academic geographers of there being either a general northward drift of surface water out of the Southern Ocean (PETERMANN, 1865) or of meridional exchanges of warm and cold surface waters across Antarctic latitudes. Zimmermann's novel portrayal of a zonally-continuous Antarctic Circumpolar Current, though correct in principle, appears fortuitous.

According to BERGHAUS (1871), his map of 1863 had several flawed features, which he did not enumerate but which indicated to him that the chart needed to be revised. The first revision (BERGHAUS, 1867) became well known in Germany, but we have been unable to locate a copy of it other than a facsimile published in the atlas by STIELER (1880) (Fig.19). A few notable changes from earlier charts exist in this one, but without explanation. For perhaps the first time the Atlantic North Equatorial Countercurrent (called the Guinea Current) was shown as extending across the entire basin. Well-defined and closed subtropical gyres were drawn in all the basins, except in the South Pacific, and the Alaska Gyre was shown more clearly than it was by Findlay. The Pacific North Equatorial Countercurrent was retained as a robust feature spanning the entire basin, and as with earlier charts the Indonesian Throughflow was shown as going from the Indian to the Pacific Ocean. Another problematical feature was the depiction of a portion of the Cape Horn Current forming an anti-cyclonic loop in the Argentine Basin entraining water from the Rio de la Plata before continuing south along Patagonia and then beneath the flow coming out of Drake Passage. This submarine current was perhaps based on temperature measurements showing a shallow maximum beneath the cold Antarctic surface waters, still measured today, which were soon used by persons such as MÜHRY (1872) to advance the theory of a subsurface poleward flow just east of Drake Passage. Confusion about the Antarctic Circumpolar Current was reflected elsewhere on the chart, such as the region southeast of Africa where warm surface currents were drawn as flowing south to the polar circle over cold eastward flow.

3.11. Gareis and Becker; J. Kayser – global surface circulation

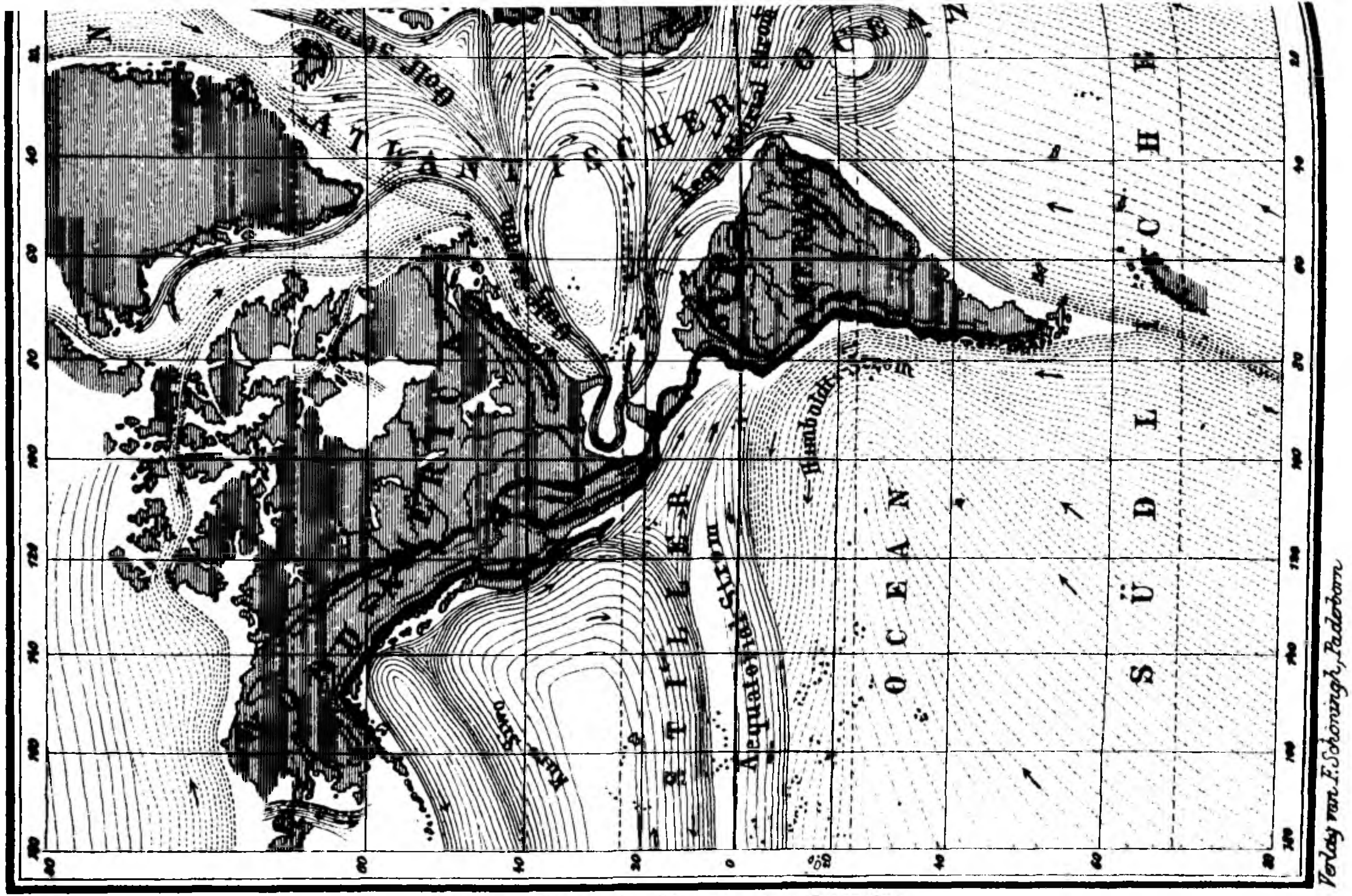
During the 1860s Austria was conducting oceanographic research from its seaport in Trieste, now belonging to Italy. Published in Trieste during the same year that Berghaus' revised map appeared was the book *Physiographie des Meeres* by GAREIS and BECKER (1867). As the title would suggest, the authors were influenced by the views of Maury, who they believed was important but sometimes wrong, which presented them with the opportunity to offer improved explanations. Among the concepts they viewed as being important was that once a coast line is reached it would be difficult for an ocean current to overcome the effects of friction and turn back out to the open sea, except near the equator where centrifugal forces would be strong enough to pull water away from the continental boundaries. Thus they disregarded evidence for a retroflection of the Agulhas Current, which appears on their map as an extension of both the Mozambique and Madagascar currents (Fig.20). Without supporting information, they described it as flowing completely around southern Africa up to the Bay of Guinea, where it replaces waters lost to the Equatorial Current. At odds with well-established facts of the Cape Horn Current flowing east, they gave the Brazil Current a southward extension all the way to Cape Horn and around into the Pacific (where it helps ships overcome unfavorable winds) to feed the Peru Current, much like the description by Zimmermann. They also reiterated Maury's concepts of the effects of temperature and salinity saying that in addition to warm water drifting poleward and cold water equatorward, equatorial evaporation would enhance the equatorward drift. They argued that centrifugal forces would deflect the northward-moving "Antarctic Drift" toward the east, which they viewed as being the same as the Connecting Current. The effects of Earth rotation were misunderstood.

Another unique map of ocean currents appeared in KAYSER's (1873) *Physik des Meeres* (Fig.21). On this map solid lines denote warm currents and dashed lines cold. Kayser described convective overturning cells, similar to Rumford's, as being the primary water movers, while also considering the effects of wind and a scheme similar to that of Gareis and Becker for the effects of Earth rotation. Except for the one in the South Pacific, the subtropical gyres all appear, and most of the major currents are shown. There is no Cape Horn Current, however, largely because MÜHRY (1872) had argued it to be only a surface response to local winds. An unusual feature shown is a direct flow from the Antarctic into the Atlantic South Equatorial Current, and a similar flow into the Peru Current appears. One might not expect it, but this chart had been copied as a representative picture of ocean circulation (e.g., ULE, 1876).

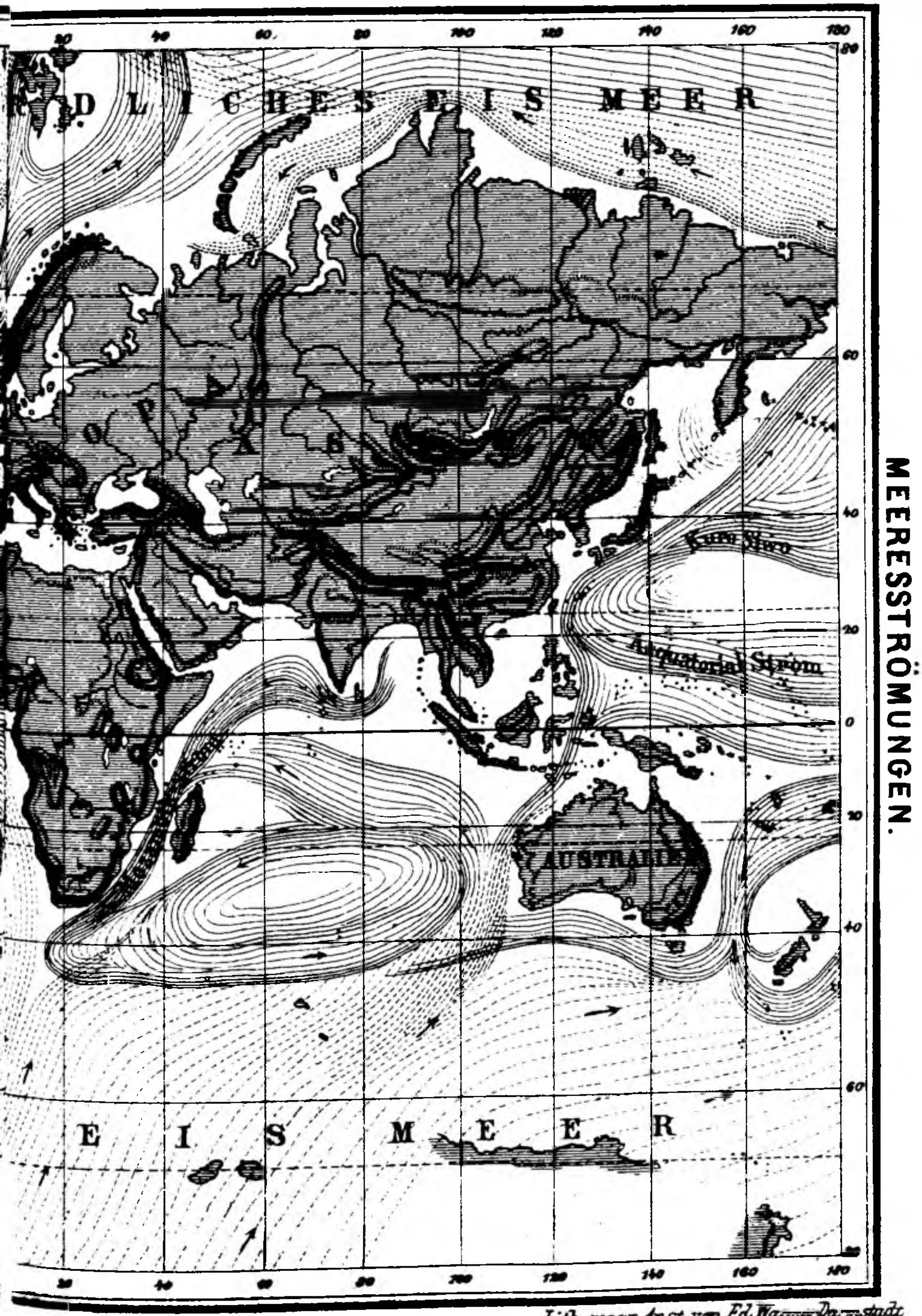
3.12. William Carpenter; Joseph Prestwich – deep circulation

The differing density characteristics between freshwater and sea-water that RUMFORD (1797) discovered were substantiated by chemists and physicists such as Marcet in 1819 and Erman in 1828 (see PRESTWICH, 1876), by Despretz in 1833 (CARPENTER, 1869), and by others later, but these characteristics were overlooked by some members of the oceanographic community. The mistake was compounded by results of temperature measurements made at depth with unprotected thermometers that were left uncorrected for the effects of pressure. On the basis of 66 readings made at various depths and latitudes, the French sea captain Dumont D'Urville (1790-1842) concluded in 1833 that at depths of about 1000m and greater in the open ocean there exist nearly uniform temperatures near 4°C, and that belts of this uniform temperature exist between the latitudes of 40° and 60°; the maximum density of freshwater occurring at this temperature lent support to the argument, an error repeated by others such as Wauchope, Wilkes, and Ross (PRESTWICH, 1876). This was echoed by the astronomer Sir John Herschel (1792-1871), who in his *Physical Geography* wrote: "In very deep water all over the globe a uniform temperature of 39° Fahr. (4°Cent.) is found to prevail, while above the level, when that temperature is first reached, the ocean may be considered as divided into three great regions or zones – an equatorial and two polar. In the former of these, warmer, in the latter colder, water is found at the surface. The lines of demarcation are of course the two isotherms of 39°F mean annual temperature" (from CARPENTER, 1869).

The impetus for studying the deep ocean came mainly from marine biologists. By the 1860s it had become widely assumed that life in the ocean was restricted to the upper 600m, but with mounting evidence to the contrary the British biologists Charles Wyville Thomson (1830-1882) and William B. Carpenter (1813-1885) succeeded in convincing the Royal Society of London and the British Admiralty to sponsor a dredging expedition to the north of the British Isles (see DEACON, 1971). The paddle-steamer *Lightning* was made available and in August 1868 the expedition was begun. In addition to dredging for marine fauna at depths considered azoic, there



Kayser, Physik des Meeres. (zu § 163 ff.)



Lith. geogr. Anst. von Ed. Wagner Darmstadt

FIG.21. World chart of surface currents reproduced from *Physik des Meeres* (KAYSER, 1873).

was the goal of obtaining deep temperature measurements that would later be corrected for the effects of pressure. The type of thermometer in common use then was a self-registering kind patterned after that invented by the Englishman James Six (1731-1793) in about 1780. Six's thermometers had internal indices that recorded the maximum and/or minimum temperatures encountered, and beginning in about 1836 various unsuccessful attempts were made to shield these thermometers from the effects of pressure (the development of deep-sea thermometers has been examined in detail by MCCONNELL (1982)).

The cruise of the *Lightning* was small in scope, but results from it were considerable in their impact. Bottom dredges were made at depths of around 1000m, and they provided ample proof of animal life existing at such depths. The outfall of this discovery led directly to other expeditions in the region, and ultimately to the circum-global expeditions of the *Challenger* (1873-1876) and the *Gazelle* (1874-1876). With respect to physics, results from the *Lightning* survey were comparably dramatic. In order to be certain of dredging in deep water, a target point for the cruise was a depression known to exist between Scotland and the Faroe Islands, now called the Faroe-Shetland Channel. This channel is the southernmost extension of the Norwegian Basin through which cold and dense waters of Arctic origin stream out into the North Atlantic, sink, and then mix with deep waters (e.g. REID, 1994). During the *Lightning* expedition, uncorrected temperatures of near 0°C were measured in the Faroe-Shetland Channel at depths of about 1000m, whereas at about the same depths less than 200km to the southwest, in the Iceland Basin on the other side of the Wyville-Thomson Ridge, were temperatures of nearly 8°C. Relatively warm water was again found after proceeding northwest to similar latitudes as where the cold water had been found, which happened to still be on the equatorward side of the SE-NW ridge.

CARPENTER (1869) revealed the results of the cruise a month later at a meeting of the Royal Society. Contrary to the prevalent thinking that water colder than 4°C could not exist in the deep ocean, he stated: "Our researches have conclusively established the existence of a minimum Temperature at least as low as 32°F (0° Cent.) over a considerable area, where the depth was 500 fathoms (914 mètres) and upwards; notwithstanding that the *surface*-temperature varied little from 52°F (11° Cent.,).."․ He then cited Purdy and Maury for other instances where similarly low temperatures had been recorded at depth in the North Atlantic. The citation to Maury was to an 1860 printing of *Physical Geography of the Sea*, in which Maury attributed a temperature of 1.6°C observed beneath the Gulf Stream as being the result of cold waters moving south to replace the overlying warm waters moving north (this may have been the first account of the deep western boundary current based on *in-situ* data). Because the thermometers Carpenter used to make his measurements were lost at sea later during the cruise, it was impossible for him to make laboratory determinations of the effects that pressure had on his readings, so he could only say that the actual minimum temperatures were probably lower still. Also, the thermometers could register only the minimum temperatures they encountered, so there was the question of where the minima actually occurred in the water column. But because of the continual increase in density of sea-water with cooling, Carpenter deduced that the coldest waters were probably at the deepest point of each cast. Referring to Humboldt as an authority about the physical necessity for deep water to sink in polar regions, Carpenter interpreted the colder water as being of Arctic origin and the warmer deep water as coming from the south. The existence of the ridge separating the two types of water was not known, so Carpenter interpreted this as a meeting of two currents from different directions within the same channel (this was more clearly stated by CARPENTER, JEFFREYS and THOMSON (1870)). He also cited observations of water being as cold as 0.8°C near 3500-m depth in the Arabian Sea and concluded that those waters were from the Antarctic. At this point he seems to have had fully in mind the idealized model of convection cells being symmetric about the equator, which of course would not obtain for the Indian Ocean because of its northern closure.

The extraordinary results of the *Lightning* expedition clearly warranted another to the region. It was made the following year, in 1869, on three legs with the survey vessel *Porcupine* (CARPENTER, JEFFREYS and THOMSON, 1870). The Miller-Casella thermometer (pressure-protected Six's thermometer) had just been invented for this work, and tests had shown that it could be relied upon to provide temperatures accurate to within 1°F (0.6°C) to depths as great as 2500m. A set of Miller-Casella thermometers was used at a greater number of locations and to greater depths than in the *Lightning* survey, and once again the contrasting warm and cold waters were found in the same regions as before; the lowest temperature measured was 29.8°F (-1.2°C) at nearly 1100m depth. Taken together, the measurements indicated to CARPENTER, JEFFREYS and THOMSON(1870) that a relatively warm layer at the surface was spreading over the entire region as an extension of the Gulf Stream, and beneath this was a clearly defined change between the cold deep waters from the Arctic and the warmer deep waters from farther south. The coldest waters in the warm area, at depths of nearly 4500m, were just over 2°C. Because of the relatively shallow sill depths between the Norwegian Sea and the open North Atlantic, which would prevent Arctic water from penetrating southward in any large quantity, and because of deep equatorial temperatures having been observed near 0°C, they suggested that deep water from the Antarctic might move northward past the equator to as far as the Tropic of Capricorn. In a lecture on "deep-sea climates" published by *Nature* in 1870, Wyville Thomson further expressed the opinion that the deep water in the northern North Atlantic had as its source the Antarctic, but Carpenter argued against it in favor of the more idealized vertical circulation being symmetric about the equator (CARPENTER and JEFFREYS, 1871).

Until this time, beginning with Rumford at the close of the previous century, observations of cold waters at depth had only occasionally been interpreted as being evidence for a deep, density-driven circulation. The concept remained relatively dormant, and at times it even had to be rediscovered. But with the publicity surrounding the results of these British expeditions, it would never again be lost from the general knowledge. This is not to say, however, that it was universally accepted. Arguments were soon made against it, most notably by the English geologist James Croll (1821-1890) who maintained that the influence of the mean winds would gradually work downward through the entire ocean and that wind alone was responsible for all currents. A brisk exchange of arguments was published in the early 1870s in a series of articles in *Nature*, at one point drawing the participation of William Ferrel. Carpenter was the main proponent of the thermohaline theory, and, like Humboldt, took the uncommon and insightful position that the thermohaline circulation coexists with the wind-driven currents. Croll, however, was uncompromising, insisting that density differences in the ocean are too small to generate currents (see DEACON, 1971). Croll's intransigence stemmed from his theories of long-term climate change that had the cycles of glaciation being the result of changes in solar irradiance (from cyclical variations in Earth's orbit) that changed wind patterns which in turn altered the oceanic circulation and the heat transported around the world by currents (see DEACON, 1993b).

Around the year 1850 the British geologist Joseph Prestwich (1812-1896) began collecting what deep-sea temperature measurements he could, which he intended to use in connection with certain geological questions. But because of the outfall from the *Lightning*, *Porcupine*, and *Challenger* expeditions, he decided to make a comprehensive analysis of those measurements that were made up to the time of the *Lightning* survey of 1868. In 1874, the second year of the *Challenger* expedition, he reported to the Royal Society the results of his analysis, while also giving a detailed historical account of the subject beginning in 1749. The measurements PRESTWICH(1876) used were made with various techniques from ships of various nations, so errors from different sources had to be dealt with. One was the error caused by pressure effects, for which, in the case of self-registering thermometers, he considered there to be enough information to make adequate corrections. Using the most reliable observations, he drew vertical sections of corrected *in-situ* temperature traversing the various basins of the World Ocean. For the Atlantic, his results tended to support the idea of cold waters from the Arctic and Antarctic flowing at depth toward the equator and meeting there, as indicated by a rise of the isotherms just beneath the warm surface layer. But for the Pacific the picture was quite different. Prestwich noted the small size and shallowness of Bering Strait and concluded that little or no cold water of Arctic origin could pass through it to the bottom of the Pacific. The uplifting of isotherms he saw in the North Pacific, and a lack of such uplifting near the equator, led him to think that the deep waters of the North Pacific were of Antarctic origin. He saw the same pattern in the Indian Ocean, and was thus led to the same conclusion about that basin as well, like Carpenter had earlier. Equatorial asymmetry of vertical convection and internal movements was being uncovered, though not yet convincingly for the Atlantic.

In January 1874 a new thermometer was patented in London by the makers of meteorological instruments, Negretti and Zambra– the reversing thermometer (see MCCONNELL, 1982). It is still in use today. Unlike self-registering thermometers that could determine only a temperature extreme that might exist somewhere in the water column, this new device could measure temperature at some fixed depth and its results could be accurately corrected for the effects of pressure. A number of reversing thermometers were immediately sent to the *Challenger* for use during the remainder of the voyage. The German *Gazelle* expedition was also underway, and Miller-Casella thermometers were used on it for the duration (HYDROGRAPHISCHEN AMT DER ADMIRALITÄT, 1888). Because the general results from those expeditions were not published until the late 1880s and 1890s, we defer discussion of them. The *Challenger* expedition has been well documented by a number of authors.

An early result of the *Challenger* expedition, concerning the vertical distribution of salinity as reported by BUCHANAN (1877), is worth noting here. He used a glass hydrometer to determine the specific gravities of sea-water samples, normalizing them to a standard temperature of 15.56°C (60°F) without regard to *in-situ* pressure or temperature. After discussing the surface values in the major oceanic basins, he presented vertical meridional sections extending through the Atlantic and Pacific oceans. In the Atlantic there appeared a layer with minimal values extending northward from the Southern Ocean to the middle northern latitudes at depths of about 1500m, which, although being erroneouslydeep because of his methods of reduction, we now recognize as the Antarctic Intermediate Water lying at depths of about 1000m. Buchanan did not speculate on the cause of this striking feature, but only thought that if the section had run far enough north that the isohalines would have become vertical as a result of convective mixing. The Pacific presented a rather confusing picture, because of the methods used, but the Atlantic section might have been used to question the idea of thermohaline cells symmetric about the equator in that basin.

3.13. Karl Zöppritz – wind stress and its downward propagation

A short while after the debates between Croll and Carpenter had subsided, Croll's arguments received a substantial boost by the work of the German fluid dynamicist Karl Zöppritz. Questions concerning the effectiveness of wind in creating surface currents and to what depth such forcing extends had until then been addressed only through rudimentary observations and qualitative reasoning. The theory of friction in fluids had, however, been developing over the previous three decades. Taking notice of the debate and the lack of a quantitative analysis of the problem, ZÖPPRITZ (1878a,b) applied to it a set of momentum and continuity equations he considered appropriate. They were written in a form familiar to us today, though without the rotational terms and in a coordinate system having x as the vertical axis. Rewritten in present-day notation, Zöppritz's momentum equation for eastward flow, for example, was:

$$\frac{du}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{\mu}{\rho}\nabla^2 u = 0,$$

where u is eastward speed, ρ is density, p is pressure, and μ is the molecular coefficient of friction for water.

Zöppritz used a near-average laboratory value of 0.0144 (in c-g-s units) for the frictional coefficient to arrive at a time-dependent vertically-diminishing profile of velocity. Solving for the profile as a function of time, ZÖPPRITZ (1878b) arrived at the conclusion "that, if the particles of the surface of the ocean of very great (properly infinite) depth, at rest, begin at a point of time t=0 to move forward with a constant velocity, half the velocity of the surface will first prevail at 100 metres depth after 239 years". He then calculated the effects of periodic variations in the winds, such as the seasonal cycles, and obtained solutions for systems evolving over thousands of years. His conclusions were "that the stationary motion proceeding from an invariable surface-velocity makes itself perceptible with linearly diminishing velocity right to the bottom in an unlimited sheet of water, while the view has frequently been expressed that the influence of such surface-currents (as, for instance, the impulse generated in the equatorial regions of the ocean by the trade-wind) extends downward to only very limited depths. Secondly, we have found that all periodic or aperiodic variability changes in the forces acting upon the surface are propagated into the depths with extreme slowness, the periodic with very rapidly diminishing amplitude. From the combination of these two propositions it follows that the motion of the main body of a sheet of water subject to periodically variable surface-forces is determined by the *mean* velocity of the surface, and that the periodic changes are perceptible only in a proportionally very thin surface stratum".

The results of Zöppritz's analysis so highly pleased Croll that he promptly had the paper translated from German into English and published in British journals (ZÖPPRITZ, 1878b; CROLL, 1879). Although Zöppritz did not mention the issue of density variations in causing oceanic motions, Croll took the results to be concrete affirmation of his views. More widely, however, the theory of Zöppritz would be interpreted as being applicable to a part of the overall circulation that also responds to thermohaline forcing. His theory was generally accepted for nearly thirty years, until EKMAN (1905) corrected the two major flaws in the way the problem of wind forcing was posed. The first flaw was the neglect of the rotational term, the inclusion of which led Ekman to discover the exponentially-decaying velocity spiral that has since been a cornerstone to theories of the wind-driven circulation. The second flaw was the use of molecular viscosity, which is grossly inadequate for parameterizing the vertical exchange of momentum in a turbulent ocean. Ekman realized that a much larger "virtual value of the coefficient" had to be used, and this remains with us today in the form of turbulent exchange coefficients. These flaws aside, Zöppritz's contribution is significant in that he was a pioneer in applying modern fluid dynamical methods to questions of the large-scale oceanic circulation.

3.14. Cato Guldberg and Henrik Mohn – geostrophy and the dynamical method

Several papers on atmospheric dynamics soon followed those by Ferrel of the late 1850s and early 1860s, among the most important being the joint analyses by the applied mathematician Cato Guldberg (1836-1902) and the meteorologist Henrik Mohn (1835-1916), both of whom were professors at the Royal University of Norway. In an essay on atmospheric motions that appeared two years before the above work of Zöppritz, GULDBERG and MOHN (1876) took a more comprehensive and general view of horizontal flow. They formulated a theoretical model establishing balances between the fundamental forces involved: "(1) the (pressure) gradient force, (2) the deflective force of the rotation of the earth, (3) the force of friction, (4) the tangential force of the motion and (5) the centrifugal force of the motion". The last two forces apply to curvilinear motion, and normally the tangential accelerations are neglected. For rectilinear flow the centrifugal force also drops out, for which case Guldberg and Mohn derived the following balances (in present-day notation):

$$\frac{1}{\rho}\frac{\partial p}{\partial n}\cos\alpha = R\upsilon,$$

$$\frac{1}{\rho}\frac{\partial p}{\partial n}\sin\alpha = 2\,\Omega\sin\phi\,\upsilon$$

where ρ is density, p is pressure, n is direction of the pressure gradient, α is the angle between n and the trajectory of an air parcel, R is the coefficient of friction, Ω is the angular velocity of Earth's rotation, ϕ is latitude, and υ is horizontal velocity. Dividing the second equation by the first yields:

$$\tan\alpha = \frac{2\,\Omega\sin\phi}{R}$$

In the frictionless case (R=0), a parcel's trajectory is perpendicular to the pressure gradient and the flow is thus parallel to isobars. This leads to the simple relationship:

$$\frac{1}{\rho}\frac{\partial p}{\partial n} = 2\,\Omega\sin\phi\,\upsilon$$

This was soon called the "baric wind-law" (i.e., MOHN, 1883), and is now known as the geostrophic relation. Ferrel conceived this balance of forces in 1856, but he never wrote it in such a clear and concise way.

In their paper of 1876, Guldberg and Mohn went on to treat curved flow, vertical motions, and some thermodynamical considerations. In GULDBERG and MOHN (1880), they performed three-dimensional analyses of ascending air in cyclones and descending air in anticyclones. The renowned Scandinavian school of dynamical meteorology had been established. From it would come the major works that have shaped twentieth-century theories of the atmosphere, many of which have

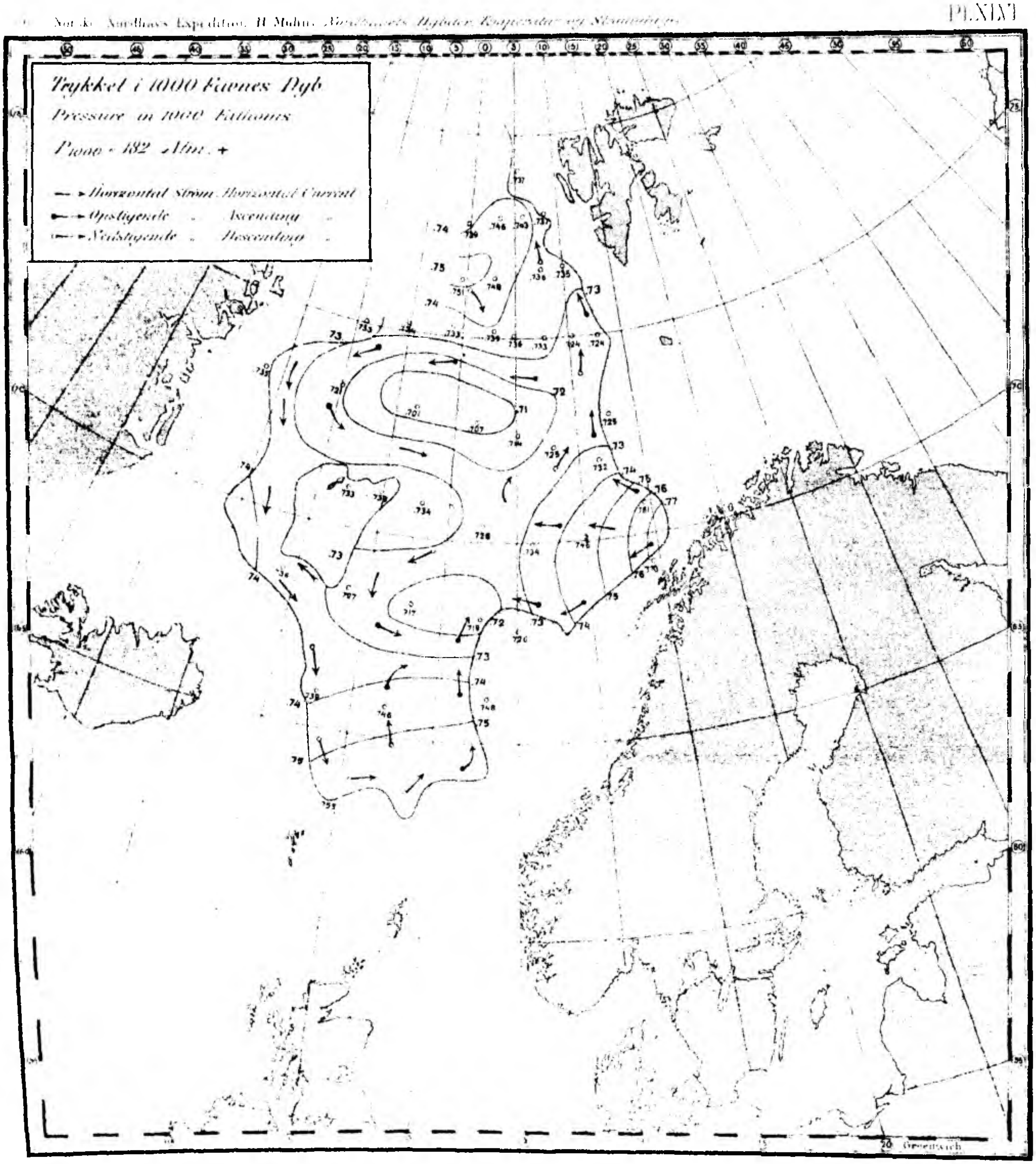


FIG. 22(a). Distribution of pressure (in units of atmospheres + 91) at 500 fathoms depth (885m) in the Norwegian Sea by MOHN (1883). Arrows denote direction of flow inferred from the geostrophic balance, except near the bottom where directions were inferred from the slopes of isopleths in vertical sections.

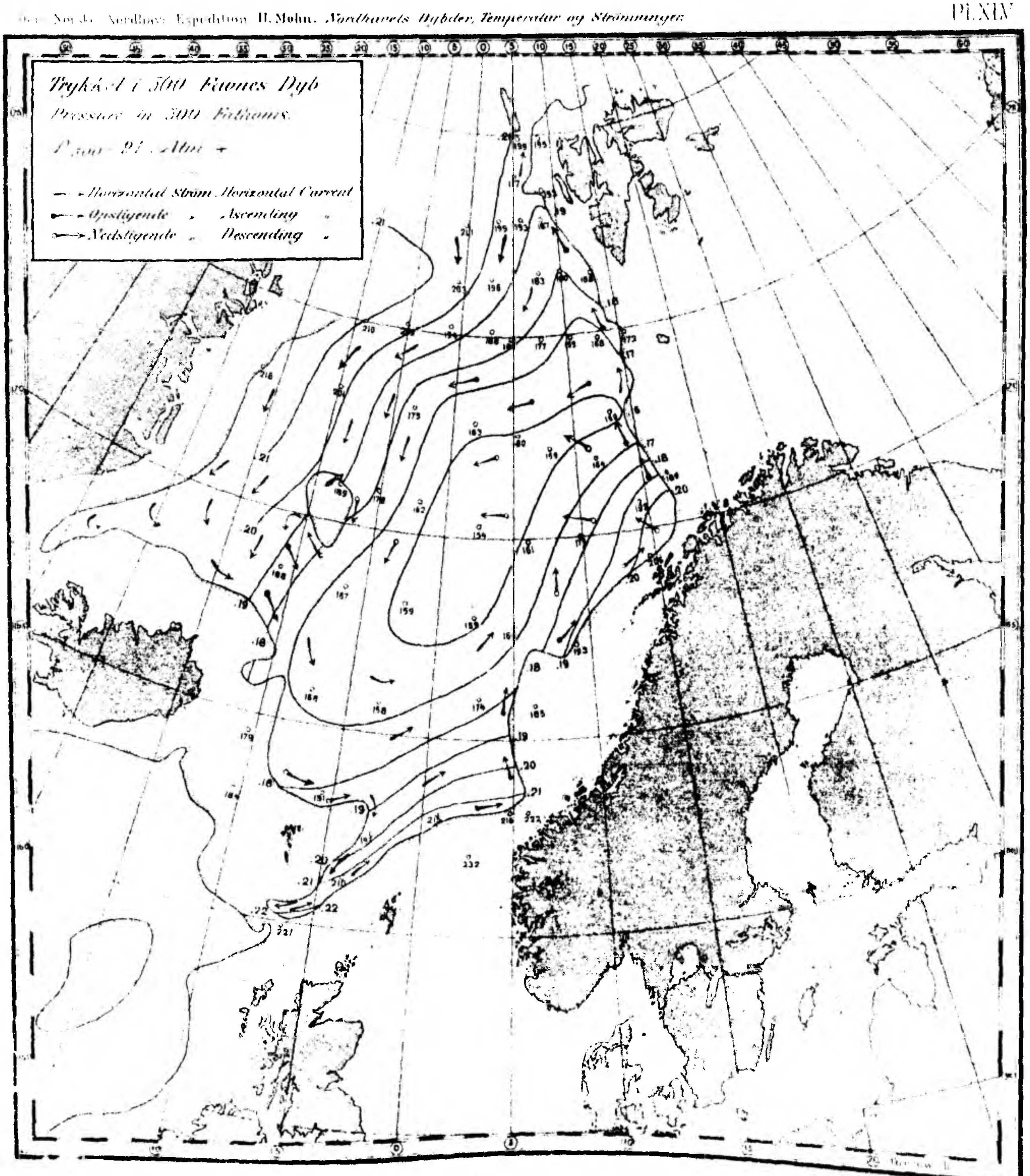


Fig. 22(b). Distribution of pressure (in units of atmospheres + 182) at 1000 fathoms depth (1770m) in the Norwegian Sea by MOHN (1883). Arrows denote direction of flow inferred from the geostrophic balance, except near the bottom where directions were inferred from the slopes of isopleths in vertical sections.

been applied to the ocean.

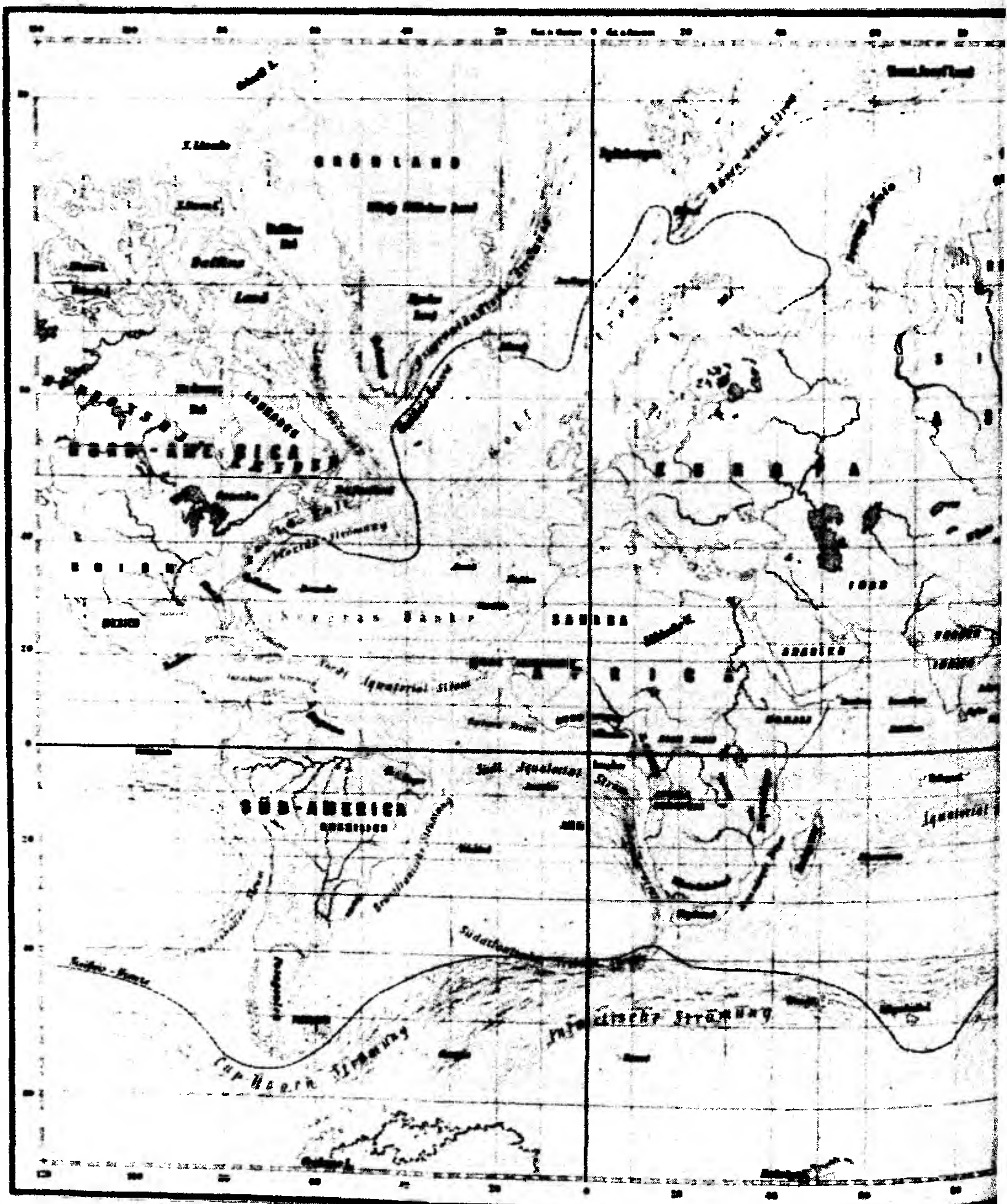
The earliest application of the Guldberg-Mohn dynamical system to the ocean was provided by MOHN(1883) when he used observations from the *Vøringen* made during the Norwegian North-Atlantic Expedition of 1876-1878. Mohn's approach was new to oceanography, and although his work is seldom cited now it was well known by those who followed him in the Scandinavian school. His method, still central to dynamical oceanography today, was to include in a model all conceivable forces important to the production of ocean currents, at depth as well as at the surface, in order to calculate flow patterns in lieu of needing to obtain direct measurements of velocity.

With the popularity of Zöppritz's theory that only the long-term mean winds are important for inducing currents, the first force to consider was that of the time-averaged surface winds. Measurements of winds over the Norwegian Sea were sparse and completely inadequate for statistical purposes, but there were measurements spanning several years of atmospheric sea-level pressure from coastal and island locations. From these, Mohn derived a field of mean sea-level pressure and then applied the baric wind-law to obtain a field of mean surface winds over the Norwegian Sea. Using distributions of atmospheric pressure to derive surface winds acting on the ocean is a common procedure today, and it seems this was the inception of the method.

Measurements of wind-induced surface currents were by then showing the ocean surface response as being 3.2% of the prevailing surface winds, a figure well within the range of what we know now to be reasonable. Mohn used this to estimate the surface currents over the ice-free ocean, and a ratio for regions covered by ice that decreased from the ice-free value at the ice edge to 0.08% at coastal boundaries. He assumed the wind-induced currents to flow in the same directions as those of the overlying winds, except near coast lines where the currents would by necessity be parallel to the coast and reduced in magnitude. The mean wind field over the Norwegian Sea is cyclonic, and so was the obtained pattern of surface circulation. Mohn then invoked the deflecting force of Earth's rotation, noting that in the northern hemisphere a moving parcel of water will maintain its direction of motion only if the sea surface slopes upward to the right of the motion. By finding slopes that would maintain the inferred surface velocities, he constructed a concave pattern for the elevation of the sea surface relative to a geoidal surface, and he argued that the effects of horizontal friction away from the coast and centrifugal forces on such scales are insignificant. He deduced that the sea surface in the middle of the Norwegian Sea, if caused only by wind-induced currents, would be depressed by 0.8m relative to the coast of Europe.

Mohn next considered the added importance of variations in density in an attempt to calculate the form the sea surface would take under the sole influence of three-dimensional density variations. The non-linear effects of salinity, temperature, and pressure on density were not known, so all he could use were simple coefficients for the individual effects. These led Mohn to calculate densities at depth that were sometimes less than those of overlying waters, which he interpreted as being signs for tendencies toward vertical motions. After integrating the inferred densities with depth, he found the sea surface had a concave shape similar to that which would obtain solely as a result of the wind field. By combining the two he arrived at a resultant sea surface lying 1.4m lower in the center of the gyre than off the coast of Norway. This is more than four times that found in the analysis by CLARKE, SWIFT, REID and KOLTERMANN (1990) (using only the density field). Mohn then derived a field of net currents at the surface, and this of course was in the pattern of the cyclonic winds.

Integrating downwards through the ocean, Mohn calculated the horizontal distributions of pressure at various depth levels. These reflected the combined effects of the distortion of the sea surface as a result of winds and the variations in density. His distribution of pressure and the associated flow field at 500 fathoms (~1000 m; Fig.22a) was qualitatively similar with his surface


GRÖNLAND
NORD-AMERICA
SÜD-AMERICA
EUROPA
AFRICA
ARABIEN
SAHARA
Sargasso Bänke
Nordl. Aequatorial Strom
Südl. Aequatorial Strom
Brasilianische Strömung
Cap Horn Strömung
Antarctische Strömung
Florida Strömung

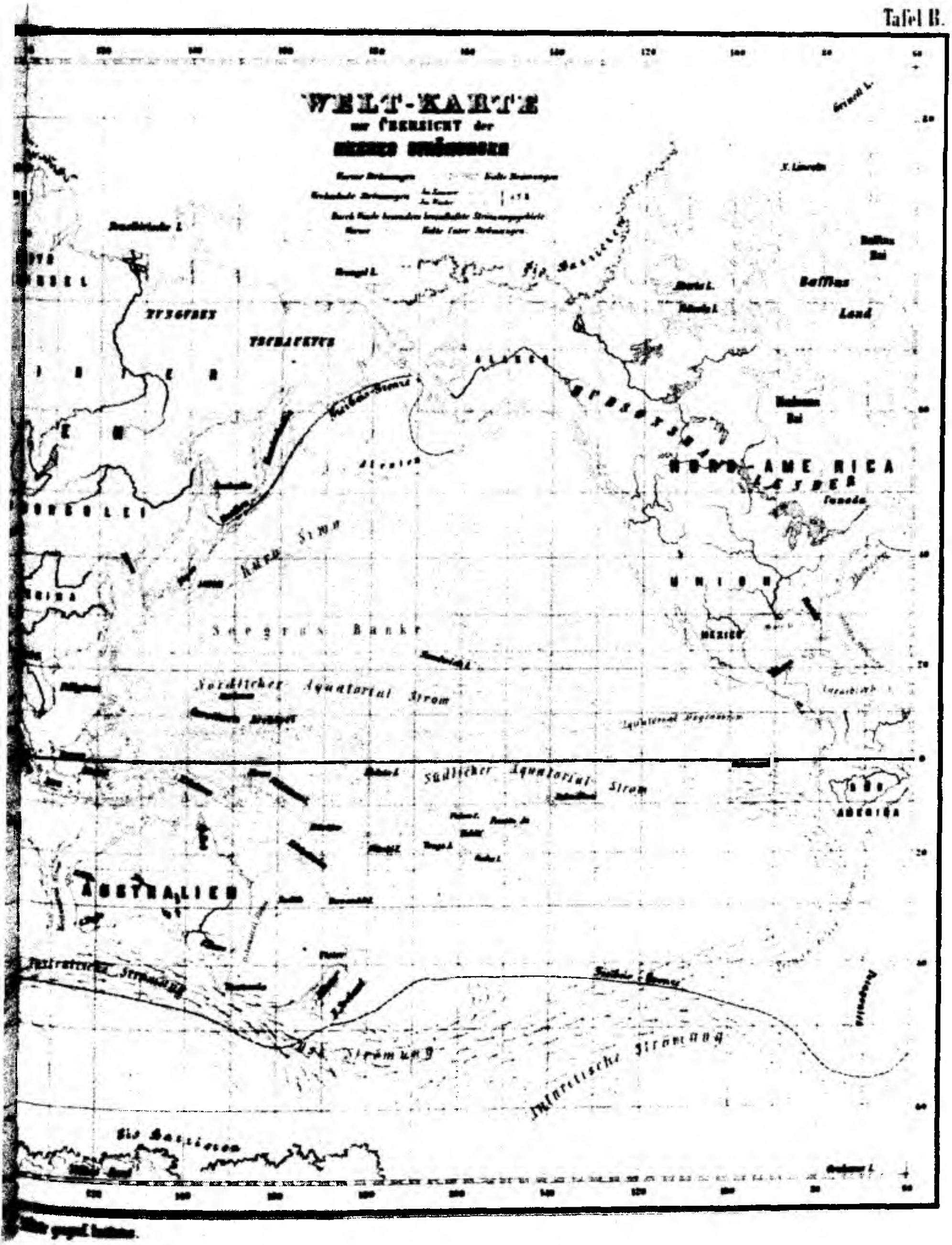


FIG.23. World chart of surface currents by ATTLMAYR and MAYER (1883)

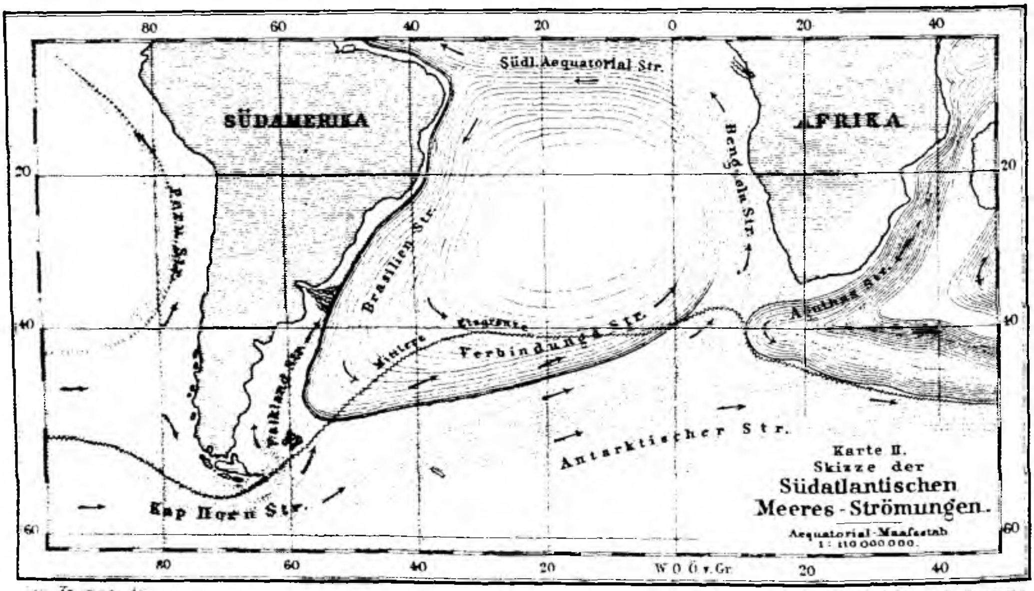


FIG.24. Chart of surface currents in the South Atlantic Ocean by KRÜMMEL (1882).

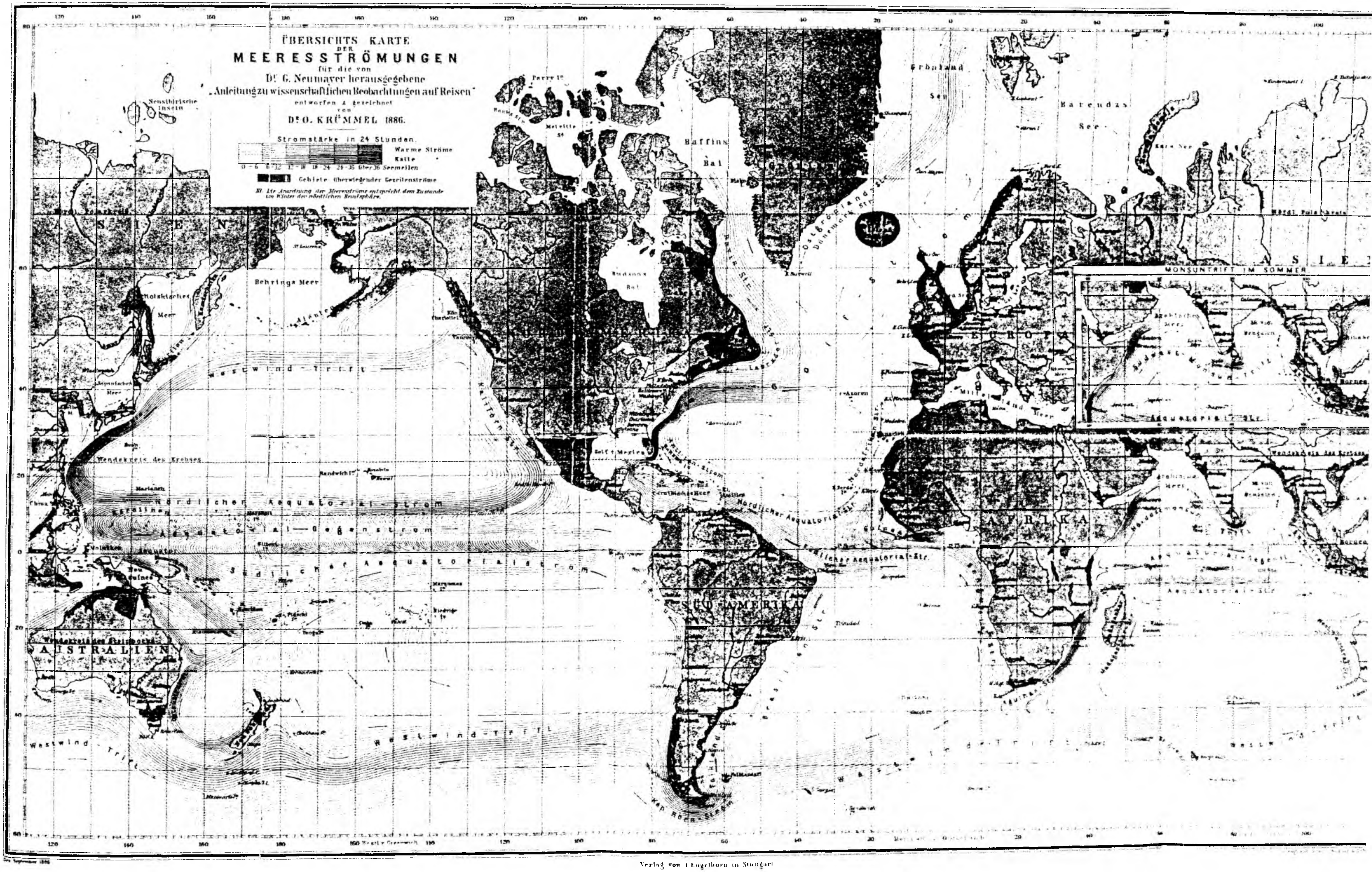


FIG.25. World chart of surface currents reproduced from *Handbuch der Ozeanographie* (KRÜMMEL 1887).

field, but at 1000 fathoms (~2000 m) variations in density had accumulated to produce a system having two lows and two highs (Fig.22b). In his chart for 1000 fathoms, the placement of the main low between Spitzbergen and Iceland and that of the high off the northwest coast of Norway are in remarkably good agreement with similar features depicted in the dynamic height field at 1000m relative to 2000m in the paper by CLARKE, SWIFT, REID and KOLTERMANN (1990).

Although we can now see some flaws in Mohn's technique, it was nonetheless an immense contribution toward modern dynamical oceanography. This was the first attempt at treating all known forces together in a single picture of ocean circulation.

3.15. Ferdinand Attlmayr and Ernst Mayer – global surface circulation

A great many advances had been made in the oceanographic sciences up to the time of Mohn's work, and a summary of the physical, chemical, biological, geological, and meteorological knowledge appeared in a single volume published by the Austrian war department. *Handbuch der Oceanographie und Maritimen Meteorologie* was prepared by professor Ferdinand Attlmayr (1829-1906) of the Royal Marine Academy and by five other contributors who were either high government officials or former ship captains. The book was intended for the use of Austrian naval officers, but it was made available to the public as well.

The circulation of the ocean was the subject of a chapter by ATTLMAYR and MAYER (1883). Their review of the literature was fairly extensive and from it they put together a map of surface currents (Fig.23). They cited as source material for their map several works published during the years 1872 to 1880, and clearly it was a much better map than those given by Gareis and Becker (Fig.20) and then Kayser (Fig.21). One of the sources cited was the chart of currents appearing in the atlas by STIELER (1880) (Fig.19), and as we have pointed out this map was a facsimile of a chart by Hermann BERGHAUS (1867). Attlmayr and Mayer did not refer specifically to Berghaus, but their newer map shows the influence of Berghaus' map. The main differences in content between the new Austrian map and that by Berghaus are that the Austrians did not attempt to show any subsurface currents, thus making the map less confusing, and that a nearly continuous, circumpolar flow of cold water was depicted in the Southern Ocean. This was the chief improvement over the Berghaus map, though it is difficult to discern in our reproduction because the original was printed in color (red for warm water, green for cold).

In the text, Attlmayr and Mayer offered few explanations of their own, and they usually presented opposing sides of contentious issues without expressing their own opinions. An interesting theory they reported was one by Zöppritz (1879) where the North Equatorial Countercurrent was attributed to two westward currents impinging on a coast which would then set up an eastward current between them. Nearly all the other ideas presented by Attlmayr and Mayer have been discussed in our previous sections, so we will not repeat them now. But a point to make is that their work, which was more a compilation than a synthesis, was a precursor to the type of all-inclusive works that would appear later.

3.16. Otto Krümmel – global surface circulation

Working at the University of Kiel in Germany during this period was Otto Krümmel (1854-1912), a professor of geography who might be considered the first research-oriented academic oceanographer in the modern sense. In an early study stemming from his doctoral work, KRÜMMEL (1877) systematically characterized seasonal changes in the equatorial regions of the Atlantic. His data base consisted largely of ship-drift and surface temperature observations, and with these he found the eastward-flowing Guinea Current to begin at a significantly more northwesterly location during the oceanic summer than winter: near 10°N; 42°W in September as opposed to 4°N; 26°W in March. We now understand this as being a description of the seasonal variability of the North Equatorial Countercurrent associated with latitudinal migrations of the atmospheric Inter-Tropical Convergence Zone. Krümmel's descriptions were qualitatively consistent with present knowledge with regards to the strength and latitude of the countercurrent, but it is now known to be a permanent geostrophic feature originating from the North Brazil Current, an aspect masked at the skin of the ocean by the prevailing trade winds.

While continuing to work with the historical data base, KRÜMMEL (1882) noted that the newest charts of the South Atlantic (the more implausible ones notwithstanding) were still showing features in much the same way as RENNELL (1832) had described them, but that contradicting information could be found on charts from the British Meteorological Office and the British Admiralty. Taking the observations of temperature (some from great depths) and ship drift in the southwestern Atlantic from more than a hundred sailing vessels and a smaller number of steamers, KRÜMMEL (1882) made the first detailed investigation of what he named the Falkland Current, now also known as the Malvinas Current. Although it had been commented upon by BERGHAUS (1837a) and sketched on charts not much later by KERHALLET (1850), there was still no consensus as to the current's permanence – it had been widely considered to be only a surface drift responding to local winds. But Krümmel determined it to be an unambiguous, deep-reaching current that originates from the northern portions of the Cape Horn Current and which exists the year around.

In the same work, KRÜMMEL (1882) traced the western and southern wall of the Brazil Current, finding that instead of reaching the Falkland Islands, as had been commonly thought, the current makes an abrupt turn to the ENE south of 45°S, and that sharp temperature contrasts exist across it to as far as 40.5°S 9°W. He also observed numerous irregularities along the length of the current and no seasonal variation in its position (which he considered uncertain because of an inadequate number of observations). This apparently was the first basin-scale, explicit description of what later came to be called the Subtropical Convergence and more recently the Subtropical Front, though a convergence of surface waters had been shown on maps in about the same location beginning with those by WILKES (1845) and FINDLAY (1853).

In summarizing his study of the currents off Patagonia in context of the larger-scale general circulation, KRÜMMEL (1882) presented a map of the South Atlantic (Fig.24), with the features in the eastern side being attributed to those he had seen on charts from the British Admiralty. Significant aspects of the map not included on earlier ones were the anti-cyclonic poleward extension of the Brazil Current he had described, and a more clearly zonal flow of the 'Antarktischer Strom' all through this sector of the Southern Ocean.

For the World Ocean, there had not been any substantive improvements to the chart by Hermann BERGHAUS (1867), nor had there been any real synthesis of concepts pertaining to ocean circulation. These shortcomings were addressed in *Handbuch der Ozeanographie* by KRÜMMEL (1887); it promptly gained international renown as the standard source for physical oceanographic information. In it Krümmel provided a global chart of the surface circulation (Fig.25) constructed from all information available, which can now be judged with overall approval. All the major currents were presented in their proper locations, and an inset was included that depicts the monsoonal cycle in the northern Indian Ocean - a new cartographical technique widely adopted and kept in use ever since. Also, the Antarctic Circumpolar Current was shown to be a zonally-continuous feature.

Krümmel was fairly well satisfied with the state of knowledge pertaining to the patterns of surface circulation, about which he provided lengthy and detailed descriptions. But the applicable theories, he thought, were still fragmentary, so he dealt with these mainly from a historical perspective. But he did describe tank experiments in which the American and African land masses were approximated and that by applying zonal winds in the tropics the general flow in the Atlantic could be simulated. He discussed the effects of Earth's rotation, including the works by Ferrel and Mohn, but from the tank experiments he was led to believe that the deflecting force is probably weak in most cases as compared with other forces.

Krümmel was still in the early part of his career when his first overview of the science was written, and he later modernized his views in a revised *Handbuch der Ozeanographie* (KRÜMMEL, 1911), which we can not go into without dealing with all the advances made during the interim. Krümmel's book of 1911 set new standards, but the one important thing that was not improved upon, nor even duplicated, was his 1887 chart of the global surface circulation. In that chart, one can visualize all the knowledge that had been acquired about the ocean's surface circulation through centuries of exploration and observation. It was a chart whose contents and style were widely emulated in publications around the world, and it still has strikingly familiar modern aspects about it to our own eyes.

At the time of Krümmel's book of 1887, concepts about the surface and deep circulations were converging on those that would become the basis of our present understanding. We therefore find this to be a fitting place to conclude our study. We hope that by discussing many of the older ideas and showing charts that appeared with them has shed light on the richness held by the early history of our science.

4. ACKNOWLEDGEMENTS

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