
CHAPTER 8

Meteorological and hydrographic support of energy-saving maritime transport

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Abstract

This section is dedicated to a comprehensive analysis of meteorological and hydro-navigational support as a key factor in optimizing maritime routes and reducing energy consumption in commercial shipping. The role of satellite technologies, automated monitoring platforms (in particular, ARGO drifters and wave glider-type gliders), numerical ocean circulation models, monsoon forecasting, and gravimetric variations in ensuring navigational safety and enhancing route planning efficiency is assessed. It is demonstrated that the integration of navigational and meteorological data allows avoidance of areas with high resistance, storm risks, or abnormal waves, leading to reductions in fuel consumption and emissions. Special attention is given to the analysis of gravitational anomalies in the Indian Ocean region and their influence on monsoon processes, which are critically important for ocean voyage planning. Technological and organizational approaches are proposed for the development of integrated hydro-meteorological support systems for maritime transport, aimed at lowering fuel consumption and supporting the sustainable development of marine transportation.

The section explores the complex interplay of meteorological, hydro-navigational, and geophysical factors that define the conditions for energy-efficient navigation within the Indian Ocean monsoon circulation zone. Particular focus is given to the influence of spatiotemporal variations in Earth's gravitational field (Δg) and geoid shape deformations on atmospheric structure, sea level, and seasonal wind activity. Evidence is presented showing the synchronization between annual Δg harmonics and the phases of monsoon circulation, providing a basis for a new paradigm of hydro-meteorological forecasting based on satellite data from GRACE and AVISO+.

It is shown that such gravitational and geoidal anomalies may serve as reliable indicators of changes in air mass and marine conditions prior to the formation

of classical barometric gradients, opening new possibilities for long-term voyage planning.

The materials of this section are interdisciplinary in nature and are intended for professionals in the fields of shipping, navigation, hydro-meteorology, oceanography, and applied geophysics. The proposed approaches form a foundation for the development of integrated systems that ensure energy-efficient shipping within the global maritime transport network.

Keywords

Maritime transport, hydro-navigation, ARGO drifters, gliders, satellite altimetry, oceanographic data, monsoon circulation, hydro-meteorological support, energy-efficient navigation, ship route optimization, Earth's gravitational field.

8.1 Introduction

The modern maritime transport system is undergoing a transformation driven by the challenges of the global energy crisis, the need to reduce greenhouse gas emissions, and increasing safety requirements in navigation. One of the key tools for achieving energy efficiency in maritime transport is the implementation of an integrated meteorological and hydro-navigational support system, which is capable not only of monitoring the current state of the marine environment but also of providing predictive data for adaptive route management.

According to research, fuel consumption during sea voyages can be reduced by up to 10–15% solely through the optimization of vessel routes based on weather conditions, currents, waves, and wind patterns [1]. Such optimization is only possible if the ship's navigational system is integrated with high-precision meteorological models, digital nautical charts, and global oceanographic data exchange platforms.

The search for new ways to reduce fuel costs, voyage time, and environmental impact requires a fundamental transformation of navigational support systems. Particular emphasis must be placed on improving methods of meteorological and hydro-navigational support for shipping – especially in open-sea operations and when crossing variable hydro-meteorological zones.

One of the fundamental directions in this context is the development of digital, dynamic routing systems that adapt to changing weather conditions, ocean currents, wave heights, and the spatiotemporal structure of oceanographic variability. These parameters are critical in determining ship resistance, the risk of accidents, and ultimately the overall efficiency of maritime transportation.

8.2 The role of hydro-meteorological forecasting in enhancing the energy efficiency of maritime transport

The availability of accurate hydro-meteorological forecasts along a vessel's route enables not only the avoidance of hazardous areas (such as cyclones, storms, or fog zones), but also the optimization of the vessel's trajectory by accounting for ocean currents, wave patterns, and wind direction. For instance, avoiding headwinds exceeding 10 m/s can reduce fuel consumption by up to 15–20% per day of navigation.

The informational support for such decisions is made possible through the integration of data from multiple sources, including satellite-based altimetry and gravimetry, forecasts of wind, currents, wave height, as well as data collected from ARGO buoys, wave gliders, and drifting platforms.

Moored buoys (Fig. 8.1) are a vital component of modern ocean observation systems. These are stationary platforms anchored to the seafloor by means of mooring systems. Their primary advantage lies in their ability to conduct long-term, continuous measurements at a fixed point in the ocean.

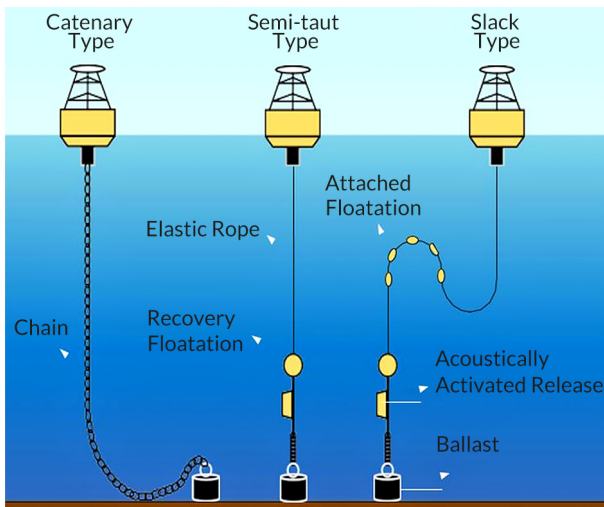


Fig. 8.1 Types of moored buoys

The use of moored buoys for oceanographic research began in the 1960s. One of the first major projects was the Barbados Oceanographic and Meteorological Experiment, conducted in 1969. This experiment involved the deployment

of a network of moored buoys in the tropical Atlantic to study ocean-atmosphere interactions.

A significant milestone in the development of moored buoy systems was the launch of the tropical ocean global atmosphere (TOGA) program in the late 1970s [2]. Within this program, a network of buoy stations was established across the tropical Pacific Ocean to investigate the El Niño phenomenon. This network, known as TAO (tropical atmosphere ocean), was later expanded to include other regions of the World Ocean [3].

Modern moored buoys are equipped with a suite of sensors designed to measure a variety of parameters:

- meteorological (air temperature, humidity, atmospheric pressure, wind speed and direction);
- oceanographic (temperature and salinity at various depths, current speed and direction);
- wave characteristics (wave height, period, and direction).

The main advantages of moored buoys include the ability to perform long-term observations at a fixed location, measure parameters at different depths, provide high measurement accuracy, and transmit data in real time.

However, moored buoys also have several drawbacks, such as high installation and maintenance costs, limited spatial coverage, and vulnerability to damage (from storms, vandalism, or collisions with vessels).

In addition, some buoys are equipped with sensors to monitor biogeochemical parameters, such as chlorophyll concentration, dissolved oxygen, and seawater pH.

A key feature of modern buoy stations is their capability to transmit data in real time via satellite communication channels. This allows timely access to oceanic and atmospheric information. For instance, TAO buoys transmit data every hour and are used for operational weather forecasting and monitoring conditions in the tropical Pacific Ocean.

Modern moored buoys can operate autonomously for extended periods (up to a year or more) thanks to energy-efficient electronics and power systems based on solar panels and other renewable energy sources. For example, ATLAS buoys (autonomous temperature line acquisition system), used in the TAO array, can function without maintenance for up to 12 months.

Oceanic drifters (drifting buoys) are an important supplement to the network of stationary moored buoys. Their primary advantage lies in the ability to cover large ocean areas at relatively low energy costs.

The history of using drifters for oceanographic research dates back to the 19th century, when so-called "message-in-a-bottle" techniques were employed to

study currents. However, a true breakthrough came in the second half of the 20th century with the development of satellite communication and positioning systems.

Modern drifters are autonomous platforms that move freely with ocean currents [4]. They are equipped with sensors for measuring sea surface temperature, salinity, and atmospheric pressure. Some models are also capable of profiling temperature in the upper ocean layers.

A typical drifter design includes (Fig. 8.2):

1. A surface buoy equipped with a GPS antenna and satellite communication system.
2. A subsurface "drogue" or sea anchor to ensure the drifter moves with the surrounding water masses.
3. Sensors for measuring temperature, salinity, and other parameters.

An important feature of drifters is the presence of a positioning system (typically based on IRIDIUM or GPS) and data transmission via satellite communication channels. This allows for tracking the trajectory of the buoy's movement and obtaining real-time information on ocean currents.

The large-scale deployment of drifters began with the U.S. coastal ocean dynamics experiment (CODE) in the 1980s [5]. This experiment provided unique data on water circulation in coastal regions.

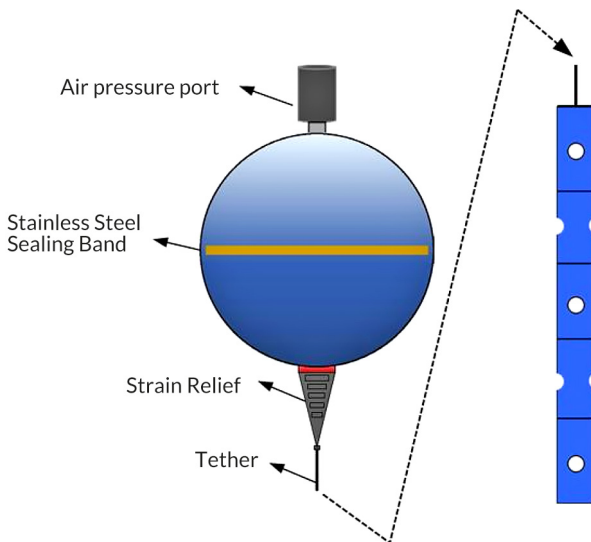


Fig. 8.2 Drifting buoy

Initially, the global network of drifting buoys consisted of several thousand units. One of the prominent initiatives is the global drifter program (GDP), which maintains a network of approximately 1,500 drifters evenly distributed across the world's oceans. These buoys supply operational data to weather services, oceanographic centers, and maritime search and rescue systems.

However, the most significant milestone in the development of the global ocean observation system was the establishment of the ARGO program (**Fig. 8.3**). This program involves the deployment of a network of autonomous drifting buoys capable of measuring vertical profiles of temperature and salinity down to depths of 2,000 meters. Currently, the ARGO program includes over 4,000 active buoys, providing global coverage of the world's oceans.

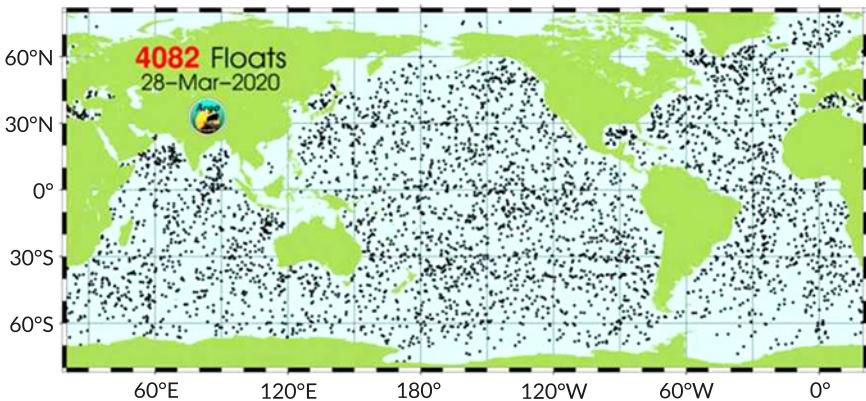


Fig. 8.3 ARGO drifter network scheme

Drifter data are widely used for validating satellite measurements and numerical ocean models. They are particularly valuable for studying surface ocean circulation, including large-scale currents, eddies, and frontal zones.

Special attention should be given to autonomous gliders, which represent a new class of ocean observation platforms. One of the most successful examples of such systems is the wave glider, developed by liquid robotics (**Fig. 8.4**).

The wave glider uses ocean wave energy for propulsion, converting the relative motion between the ocean surface and the calmer subsurface waters into forward movement. Solar panels supply power to onboard electronics, sensors, and communication systems. This hybrid energy system allows the vehicle to operate for several months without the need to return to base.



Fig. 8.4 Wave glider unmanned surface vehicle

The wave glider is equipped with a wide range of sensors:

- meteorological and oceanographic instruments;
- seismic sensors for detecting earthquakes and tsunamis;
- video cameras and acoustic systems;
- environmental monitoring systems.

Gliders provide valuable data from hard-to-reach areas of the ocean and enable long-term observations with minimal operational costs. They are particularly effective for studying mesoscale processes and monitoring changes in the oceanic environment.

Satellite technologies play a key role in modern ocean observation systems. They provide data with global coverage and high temporal resolution.

The history of satellite ocean observation began in the 1960s with the launch of the first meteorological satellites. However, a true breakthrough occurred during the 1970s and 1980s with the development of dedicated oceanographic satellites.

The main types of satellite sensors used for ocean studies include:

- radiometers, which measure sea surface temperature;
- altimeters, which determine sea surface height;
- scatterometers, which measure wind speed and direction near the surface;
- spectroradiometers, which assess ocean color (for evaluating chlorophyll concentration).

Satellite altimetry is one of the most important methods of ocean remote sensing [6] (Fig. 8.5). It allows the measurement of sea surface height with an accuracy of a few centimeters. Based on these data, sea level anomalies, geostrophic currents, and wave parameters can be determined. The principle of satellite altimetry is based on measuring the time it takes for a radar pulse to travel from the satellite to the ocean surface and back. Knowing the exact coordinates of the satellite makes it possible to calculate the sea surface height. Modern altimeters, such as those onboard

the JASON satellite series, provide sea surface height measurements with an accuracy of 2–3 cm.

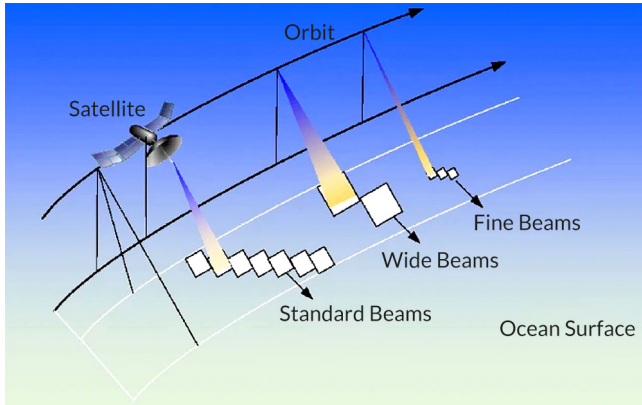


Fig. 8.5 Remote sensing via satellite

An important aspect of satellite measurements is the need to account for multiple sources of error, such as atmospheric interference, satellite orbit inaccuracies, and others. To address this, advanced data processing algorithms have been developed.

Modern satellite systems are capable of measuring the following ocean parameters:

- sea surface temperature (accuracy: 0.3–0.5°C);
- surface salinity (accuracy: 0.2–0.4 psu);
- sea surface height (accuracy: 2–4 cm);
- near-surface wind speed (accuracy: 1.5–2 m/s);
- wave height (accuracy: 0.5 m or 10%);
- chlorophyll concentration (accuracy: 30–50%).

A key direction in satellite technology development is the deployment of satellite constellations, which enhances the spatial and temporal resolution of measurements. An example is the JASON system for altimetric measurements, which includes multiple satellites operating in orbit simultaneously.

Main advantages of satellite methods:

- global coverage;
- high observation frequency;
- capability to collect data from remote and hard-to-access areas;
- long-term measurement stability.

Limitations of satellite methods:

- limited spatial resolution;
- atmospheric influence on measurements;
- complexity of calibration and data validation;
- high cost of satellite development and launch.

An analysis of the current state of ocean observation technologies makes it possible to outline the main directions for their further development.

Improvement of sensors and measuring systems. This will increase the accuracy of observations and expand the range of measurable parameters. A promising direction involves the development of new types of sensors, including chemical and biological sensors for ecosystem monitoring.

Advancement of power supply systems for autonomous platforms. The use of more efficient renewable energy sources, such as solar panels, will extend the autonomous operating time of buoys and drifters. For example, systems are being developed that harness wave energy to power buoys.

Improvement of communication and data transmission systems. This will enable the transfer of larger data volumes in real time. Promising solutions include next-generation satellite communication systems and the development of underwater acoustic networks for data transfer.

Development of new types of ocean observation platforms. A promising area is the creation of autonomous underwater vehicles such as gliders, capable of long-term missions with minimal energy consumption. These vehicles can travel thousands of kilometers and periodically surface to transmit data.

Enhancement of data processing and analysis methods. The application of machine learning and artificial intelligence will enable more efficient processing of the large volumes of data generated by different observation systems. This is especially important for integrating multisource data and identifying complex interrelations in ocean processes.

Integration of various observation systems into a unified global network. This will provide a more comprehensive and accurate view of the ocean's state. A key step in this direction is the creation of a global ocean observing system that combines data from different national and international programs.

A promising direction is the development of coastal observation systems that integrate various types of sensors – from bottom-mounted stations to radar systems. These systems provide detailed information about coastal zone processes, which is crucial for managing coastal resources and ensuring maritime safety.

International cooperation plays a vital role in the advancement of ocean observation technologies. An example is the global ocean observing system, which unites

the efforts of many countries in building a comprehensive monitoring network for the world's oceans.

The formation of monsoonal circulation, driven by changes in the Earth's gravitational field, provides a unique foundation for long-term meteorological forecasting in the Indian Ocean region. The use of high-precision satellite data on Δg variations (from GRACE) and sea level (from AVISO+) makes it possible to identify the sinusoidal nature of changes underlying climatic seasonality.

These periodic phenomena have direct practical significance for the transportation sector. Incorporating them into route planning models enables proactive avoidance of high wave activity zones, reducing fuel consumption by minimizing resistance from strong winds and rough seas; optimal scheduling of voyage start and end times, synchronizing operations with the most energy-efficient navigation conditions; adaptive adjustment of vessel draught and engine performance settings based on expected atmospheric pressure and sea state values.

Thus, hydro-meteorological forecasting based on fundamental physical and geophysical patterns is a key factor in the energy-efficient operation of maritime vessels.

8.3 Climatic features of the Indian ocean region and navigational risks

The tropical zone of the World Ocean, particularly the northern part of the Indian Ocean, is characterized by relatively stable solar insolation and the absence of significant barometric gradients, which contributes to the formation of persistent trade winds. However, during the summer months (June–August), strong southwesterly monsoon winds develop, reaching speeds of up to 14 m/s, generating waves as high as 7 meters. These conditions significantly complicate navigation, increase fuel consumption, and elevate risks for vessels and crews.

For effective energy-efficient maritime navigation, it is critically important not only to forecast the onset and end of the monsoon season but also to understand the underlying physical mechanisms that drive monsoonal circulation. This knowledge allows vessel routes to be adapted to expected weather scenarios, thereby reducing fuel consumption and enhancing navigational safety.

The Indian Ocean region – particularly its northern sector is a unique maritime area in terms of climatic conditions, exhibiting a pronounced seasonal variability of atmospheric processes. The main climate-forming factors are monsoonal circulation and the complex interaction between oceanic and atmospheric systems, amplified by geophysical factors such as variations in the Earth's gravitational field and geodynamic deformations.

For most of the year, the region is dominated by trade winds – steady and predictable winds that create a stable navigational environment. However, during the summer period (June–September), the southwest monsoon prevails, bringing strong wind-driven waves, storms, and powerful currents. Sea states can reach 6–7 meters in wave height, with wind speeds of 12–14 m/s. Such conditions considerably complicate vessel operations and, crucially, lead to increased fuel consumption due to added resistance and maneuvering efforts.

The lack of accurate long-term forecasts regarding the onset, peak, and termination of the monsoon season forces vessels to select conservative routes, increasing bunker fuel expenditures, voyage duration, and diminishing the efficiency of global logistics chains.

In this context, hydro-meteorological forecasting serves as a critical tool for ensuring energy-efficient maritime transport. Its role is not only to provide warnings about adverse weather conditions but also to deliver detailed analytics regarding:

- expected changes in wind and wave fields;
- sea surface temperature and convective activity;
- seasonal shifts in circulation systems (monsoons, cyclones);
- upwelling and downwelling currents that influence vessel draught and speed.

The application of accurate forecasts in navigational planning allows for optimizing ship routes considering meteorological factors, reducing excess fuel consumption by avoiding wave-prone zones and headwinds, and improving cargo handling efficiency by coordinating port operations with available safe approach windows.

Particular attention should be given to incorporating satellite altimetry and gravimetry data into forecast models. These allow for predicting not only atmospheric conditions but also deeper physical and geodynamic changes (Δg) that precede or accompany monsoonal activity. This opens the possibility for long-term, annual cyclic forecasts, which can be used in strategic fleet operations and voyage planning for large vessels.

In summary, the Indian Ocean region requires the integration of traditional hydro-meteorological support with modern satellite and geophysical forecasting systems to achieve maximum energy efficiency in maritime transport.

This approach enables not only cost reduction but also a significant decrease in greenhouse gas emissions, aligning with the IMO's strategic environmental goals.

The formation of monsoonal circulation has long been a subject of debate among meteorologists, climatologists, and oceanographers. The classical scientific approach has centered around two main hypotheses: the thermal hypothesis and the dynamic hypothesis, which for centuries have served as the foundation for constructing synoptic models and forecasts.

The original "thermal hypothesis" of monsoons, first proposed by Edmund Halley in 1686, interpreted the monsoon system as a large-scale land-sea breeze driven by differential heating between the continent and the ocean. This concept formed the foundation for further development by other climatologists, who described monsoonal circulation as a component of a large-scale thermal system. However, modern research – particularly the work by Wang et al. – demonstrates that while land-sea thermal contrast plays a role, it is insufficient to fully explain the complexity of monsoonal behavior [7]. Their study highlights the crucial importance of seasonal migration of the Intertropical Convergence Zone, planetary circulation patterns, and energy redistribution processes. These dynamics go far beyond the explanatory scope of the classical thermal model and are essential for achieving the level of forecasting precision required for modern energy-efficient maritime routing.

An alternative to the thermal concept was the dynamic hypothesis, introduced in the 20th century. This approach views the monsoon as a heat engine operating between two sources with different thermal capacities – the ocean and the landmass. It emphasizes not only the temperature gradient but also the movement of air masses under the influence of Coriolis forces, orography, Earth's rotation, hydraulic effects, and convective processes [8].

The expansion of the dynamic approach was made possible through the work of researchers such as Lineykin, Gandina, Khromova, and Riehl, who proposed considering cross-equatorial flows, the influence of orographic barriers (notably the Himalayas), and the dynamics of the upper troposphere. For example, the formation of jet streams plays a crucial role in the initiation of monsoons.

Taken together, the classical hypotheses have enabled the formulation of a general understanding of the monsoon phenomenon. However, they do not provide the necessary levels of precision, spatial coverage, or seasonal validation required by the maritime sector in the face of climate change and the growing need for energy efficiency.

From a maritime transport perspective, classical hypotheses of monsoonal circulation formed the foundation for the first operational forecasting models used by marine meteorological services. However, the limited accuracy of these models forces operators to incorporate larger speed and fuel reserves into voyage planning, implement redundant routing in cases of expected unstable weather, and avoid transits through certain zones under conditions of uncertainty.

Such measures are in direct conflict with the principles of modern energy efficiency. Therefore, it is essential to supplement classical models with new parameters – such as gravitational variability and satellite-derived geoid deformation data, which are analyzed in the following sections.

8.4 Geophysical factors of monsoonal circulation formation in the context of hydro-meteorological support for energy-efficient shipping

Modern science is increasingly focusing on the study of fundamental geophysical factors that influence global atmospheric circulation, particularly the formation of monsoons. One of the most significant of these factors is the spatio-temporal variability of the Earth's gravitational field (Δg). This phenomenon is directly related to mass exchange and deformation processes within the mantle, tectonic activity, and the deep internal structure of the Earth.

In the Indian Ocean region – especially in the Arabian Sea – extreme negative anomalies in gravitational acceleration are observed. These anomalies vary throughout the year and exhibit a clear annual periodicity (**Fig. 8.6**). It is known that the air mass over the region loses hydrostatic equilibrium under the influence of decreasing Δg , which leads to a reduction in the weight of the atmospheric column and, consequently, to the formation of wind flows even in the absence of a pronounced barometric gradient [9].

Alongside gravitational variations, changes in the shape of the geoid lead to fluctuations in sea level ranging from several tens of centimeters or more. These variations have substantial practical implications for forecasting storm surges and set-down phenomena, adjusting vessel draft, and evaluating additional resistance to motion caused by elevated wave activity.

Satellite altimetry (AVISO+) and gravimetry (GRACE) data confirm a statistically significant correlation between seasonal changes in Δg and sea surface height in the Goa region. A 15-year analysis yielded a correlation coefficient of $R = 0.73$ between Δg and sea level.

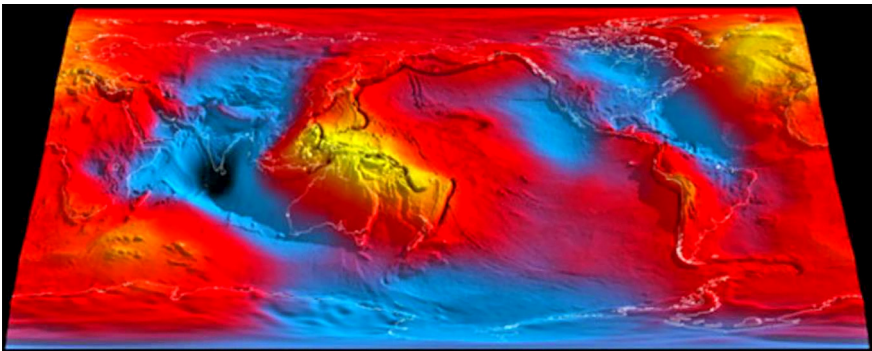


Fig. 8.6 Map-scheme of the Earth's gravitational field

Incorporating gravitational variability into hydro-meteorological support systems enables the development of multi-annual forecasts of circulation activity with a high degree of reliability. This offers several practical advantages for energy-efficient navigation, including:

- the ability to define seasonal "windows" for transit through monsoon zones with minimal fuel consumption;
- dynamic route adjustments based on geoid topography changes and associated hydrodynamic conditions;
- forecasting areas of potentially unfavorable sailing conditions even before atmospheric instability manifests.

Scientific research confirms that gravitational anomalies in the Indian Ocean region are neither accidental nor isolated. They originate from deep Earth processes, particularly the ascent of hot mantle material beneath the African tectonic plate. This mantle plume, moving northeastward, causes a geoid depression in the Indian Ocean region and thereby disrupts traditional models of atmospheric statics [10].

Understanding these processes lays the groundwork for the creation of a comprehensive navigational analytics system that accounts not only for surface meteorological conditions but also for planetary-scale geophysical parameters. This is especially important for planning voyages of large-tonnage vessels, forecasting prolonged periods of poor navigation conditions, and assessing the feasibility of routes in terms of fuel efficiency.

Thus, hydro-meteorology in the 21st century holds the potential to evolve from a local synoptic science into a global, physics- and gravity-based forecasting discipline. This new paradigm integrates satellite Δg data, geoid deformation models, conventional wind, wave, and precipitation forecasts, and digital atmospheric and ocean circulation models.

Such an integrated approach enables the design of flexible and precise maritime routes that are not only safe but also optimized in terms of fuel consumption – a critical requirement for modern shipping amid global climate challenges and mounting pressure to reduce CO₂ emissions.

8.5 Synchronization of Δg variations and seasonal monsoon dynamics: implications for energy-efficient shipping

One of the most compelling indications of the gravitational nature of monsoonal circulation is the clear seasonal synchronization between changes in gravitational acceleration (Δg) and the dynamics of atmospheric processes within monsoon

climate zones. Thanks to high-precision satellite observations (GRACE, AVISO+), quantitative data have confirmed that the most significant Δg variations occur on an annual cycle, precisely aligned with the onset and cessation of both the summer and winter monsoons (Fig. 8.7).

In the region of India's western coast (Goa), an analysis of the time series of Δg and sea level variations for the period 2002–2017 revealed the following:

- an annual periodicity in the spectra of both parameters;
- a high level of coherence (0.96) between seasonal fluctuations of Δg and the shape of the geoid;
- a phase shift of 18° , indicating a stable and predictable lead of one variable over the other [11].

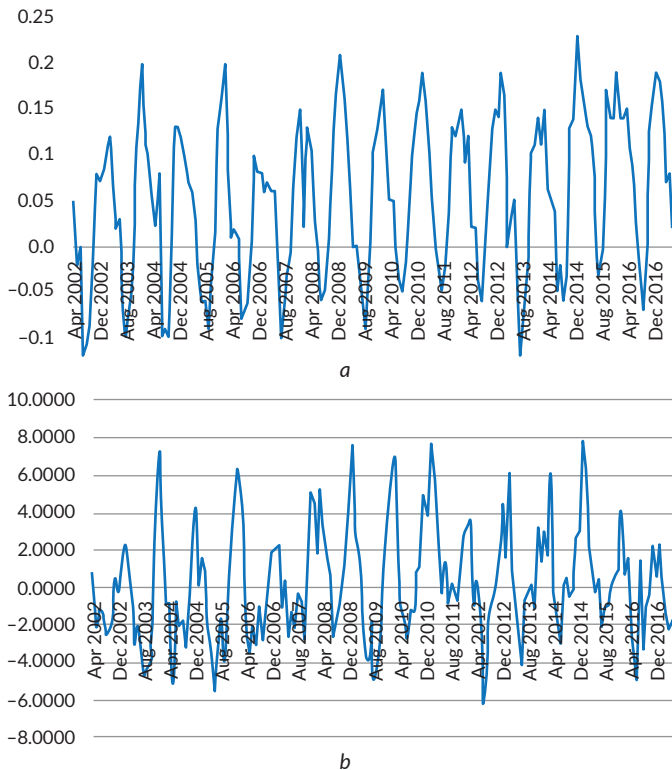


Fig. 8.7 Temporal variations of (a) geoid shape and (b) gravity in the area of the Western Coast of the Indian Peninsula (Goa Province, India)

These results make it possible to develop a predictive model in which the detection of a Δg change can serve as an early indicator of the upcoming strengthening or weakening of monsoon winds.

When gravitational acceleration decreases in a given region, the weight of the atmospheric column also decreases. This causes local disruptions in hydrostatic equilibrium without the necessary formation of a barometric gradient. In response, the atmospheric system activates self-regulation mechanisms through the movement of air masses, resulting in wind flows – monsoons.

During the summer monsoon period, Δg shows a negative anomaly that stimulates the inflow of air from the ocean toward the land. In winter – conversely – Δg increases, the weight of the air grows, and winds form in the opposite direction. Thus, Δg acts as a physical trigger for monsoon exchange, in much the same way that temperature activates thermal convection.

Incorporating Δg monitoring into navigation and meteorological analysis enables:

- forecasting changes in wind direction and speed several weeks in advance;
- predicting sea level at ports of arrival and departure;
- identifying in advance the periods when transit through monsoon zones would be excessively costly or dangerous;
- integrating the annual cycle of Δg variations into fleet route planning and voyage scheduling, thereby optimizing fuel use.

Since Δg fluctuations are globally synchronized phenomena and have a planetary nature (their influence can be simultaneously observed in the American, African, and Asian monsoon regions [12]), they can be employed for unified strategic planning of global shipping. This opens new opportunities for interregional coordination of logistic routes (for example, synchronization of cargo flows between the Indian Ocean and the South China Sea), the development of seasonal global maps of maritime risk and energy consumption, and the enhancement of decision support systems (DSS) for navigators.

As shown in previous sections, gravity field variations in the Indian Ocean region are often linked to geodynamic activity of the African tectonic plate (**Fig. 8.8**). In particular, compression of the plate in 2001–2002 was accompanied by the emergence of an anomalous weather phenomenon – nighttime condensation of water vapor over the Sahara Desert, associated with large-scale moisture transport [13].

These geophysical processes have long-term implications for fleet energy consumption. For example, the 2002 drought in India (**Fig. 8.9**) was a consequence of changes in Δg , which disrupted the usual monsoon circulation. This led to alterations in ocean currents, wind patterns, and sea levels, resulting in prolonged voyage durations, increased fuel consumption, and the need for emergency route adjustments.

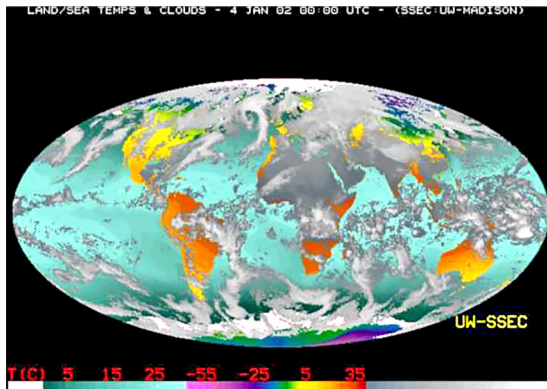


Fig. 8.8 Depiction of the compression process of the African plate during extreme geodeformations (13.11.2001–18.01.2002)

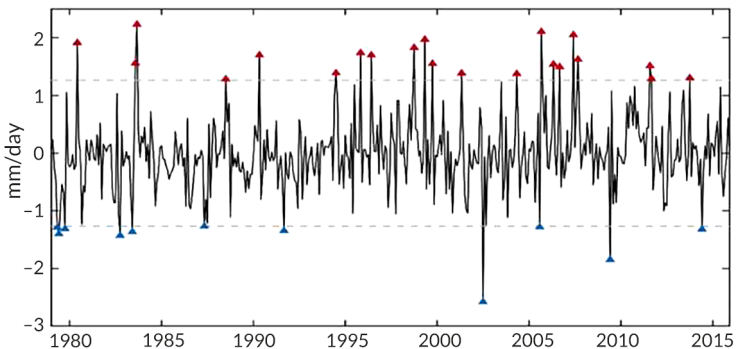


Fig. 8.9 Monthly-averaged daily precipitation in India (dotted lines represent 2 standard deviations) within the rectangular zone 10°N–30°N and 60°E–95°E

The use of satellite altimetry (AVISO+) and gravimetry (GRACE) enables the development of highly accurate synchronized models of gravitational variations and geoid changes that affect both the ocean and the atmosphere. For instance, in the Goa region, a strong correlation has been recorded between the annual harmonics of Δg and sea level ($R = 0.73$).

Such data make it possible to implement automated alerts for the onset and end of the monsoon season, dynamically adjust routes in response to predicted storm surges or water withdrawals, and model the most energy-efficient trajectory based on forecasted sea state, atmospheric pressure, and gravitational field conditions.

8.6 Altimetry and gravimetry: a new paradigm in hydro-meteorological analysis

Satellite altimetry (AVISO+) enables highly accurate measurement of sea level height, taking into account the influence of wind, atmospheric pressure, and ocean currents. In contrast, gravimetry (GRACE) provides unprecedentedly precise information on variations in the Earth's gravitational field (Δg), which indirectly reflect processes occurring in the Earth's interior and changes in the mass balance of the atmosphere and hydrosphere (Fig. 8.10).

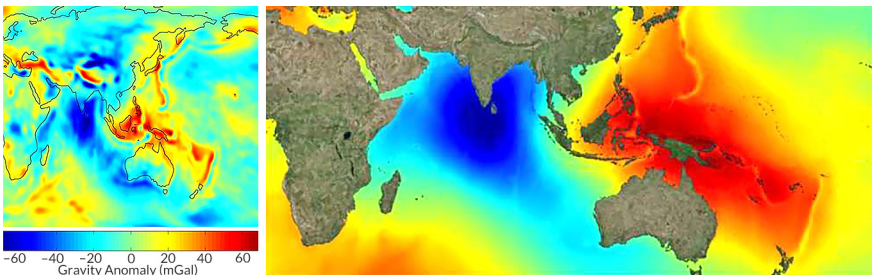


Fig. 8.10 Maps of Earth's gravity field anomalies (mGal) and geoid shape anomalies, i.e., mean sea level (m)
Source: [14]

Unlike classical meteorological models, which have temporal limitations of 5–7 days and require frequent updates, gravitational signals exhibit stable annual periodicity. This allows the development of long-term predictive scenarios for route planning.

Integrating AVISO+ and GRACE data into hydro-navigational support systems enables the following:

- forecasting the development of surge and seiche currents along coastlines and in narrow straits, which is essential for optimizing vessel speed and draft;
- detecting sea level anomalies prior to storm onset, allowing for preemptive reduction of hull and main engine loading;
- calculating optimal port and strait entry windows, minimizing energy consumption during maneuvering;
- identifying critical navigational points where decreased Δg signals a potential drop in atmospheric pressure and, consequently, increased storm activity.

A major advantage of satellite technologies is their global coverage, including remote oceanic areas where traditional meteorological stations are either absent

or operate with low spatial resolution. This enables high-precision monitoring of monsoon activity in open-sea areas (e.g., between the Somali Current and the Indian subcontinent). It also makes it possible to create regional maps of forecasted gravitational instability, facilitating weather prediction weeks in advance and integrating data from multiple satellite missions to build robust multiparametric models for marine navigation.

Data from AVISO+ and GRACE satellite missions can already be integrated into the following systems:

- ECDIS (electronic chart display and information systems);
- SPOS (ship performance optimization system);
- Voyage optimization platforms (e.g., Wärsilä, StormGeo, etc.).

This integration allows shipmasters and logistics planners to model the most energy-efficient routes in real-time based on sea state and expected currents, to adjust sailing speed according to forecasted wave height and pressure, and to modify route waypoints to avoid hazardous or high-resistance areas.

In conclusion, the use of satellite data is not only a tool for enhancing the accuracy of meteorological forecasts but also a key component of energy-efficient voyage management. It directly impacts fuel consumption, voyage completion times, and the overall environmental footprint of maritime transport.

8.7 Conclusion

First and foremost, it should be noted that modern ocean monitoring systems are based on the integrated use of various technologies, including both autonomous buoy stations and satellite remote sensing systems of the ocean surface. This integration ensures the acquisition of high spatial and temporal resolution data on ocean conditions.

Moored buoys play a key role in conducting long-term observations at fixed points in the ocean. Their data are indispensable for calibrating satellite measurements and validating numerical models. Ocean drifters, in turn, provide a cost-effective means of collecting data on temperature, salinity, and currents across large areas. The global drifter network has become a critical component of operational oceanography, particularly valuable for studying surface ocean circulation.

Satellite technologies offer unique opportunities for global coverage and high observation frequency. They enable the measurement of a wide range of parameters, including sea surface temperature, sea surface height, wind speed, and chlorophyll concentration. Satellite data are indispensable for studying large-scale processes

in the ocean but have limited spatial resolution and require complex algorithms for data processing and interpretation.

The conducted study allows drawing several important conclusions regarding the impact of gravitational anomalies in the Indian Ocean region on the formation of monsoon circulation and the consequences of this phenomenon for maritime fuel consumption. The annual periodicity of Earth's gravitational field in the Arabian Sea region (Δg) is synchronized with seasonal variations in the geoid shape, which alters the weight of the atmospheric air column and, consequently, initiates or terminates monsoon winds. This provides a foundation for long-term weather forecasting.

Recorded sea level anomalies that contradict expected results based on wind effects (storm surges or seiches) indicate the presence of alternative mechanisms of barometric gradient formation. These mechanisms have a gravitational origin and must be taken into account when calculating the optimal balance of ship draft, speed, and propeller regime.

For the first time, a high level of coherence (0.96) between the annual harmonics of Δg and the geoid shape has been confirmed. This opens up prospects for the creation of a comprehensive navigational-predictive system that integrates hydro-meteorological, satellite, and geophysical data. Geodynamic processes beneath the African plate have an indirect influence on meteorological conditions in the Indian Ocean, creating the need for transcontinental analysis of satellite information to accurately model the navigational environment.

The proposed approach may form the basis for a new generation of energy-efficient maritime navigation management systems, which will consider not only local weather conditions but also fundamental factors that shape global atmospheric circulation.

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