# Measurement, Reporting, and Verification (MRV) Protocol for Natural Ocean Carbon Cycle Management by ECOPIA Marine Ltd.: V1.0

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## Contents



## 1. Version History

This document is a working draft of ECOPIA™'s approach to the Measurement, Reporting, and Verification (MRV) of natural atmospheric carbon dioxide drawdown and management via pelagic ocean tele-illumination, Version 1.0. The document will be refined and improved as both ECOPIA™'s and the global oceans community learn through continued research and experimentation both in the laboratory and in the field. To date, the history of this MRV Protocol is as follows:
Version 1.0 - Completed August, 2023.

## 2. Background

The consideration of the principles behind ECOPIA™ (Earth Climate Optimisation Productivity Island Array) began in 2010 by MyOcean Resources Ltd. This work, mainly theoretical, intensified in March 2020, and ECOPIA Marine Ltd. was formed in 2022. Presentation and simple method tests demonstrating the vertical 'piping' of light were carried out in 2011 and through 2021/2, culminating in the demonstration of the induced growth of algae underwater. Modelling studies also showed tele-illumination was one of the few, if not the only, marine based NBCCMS (Nature Based Carbon Cycle Management Solutions) that is proven to work. ECOPIA Marine Ltd. intends to begin operational field programmes in 2023/4 to begin net carbon dioxide removal (CDR) from the atmosphere through the tele-illumination of Ocean desert regions.

A rigorous, scientific and repeatable MRV protocol, that is agreed by both the provider (ECOPIA Marine Ltd.) and customers, supported by ocean science and technology, is required to ensure that CDR is appropriately measured, quantified, monitored and audited. CDR will be verified by independent 3rd parties, and open to further scientific research, to ensure compliance with this MRV protocol.

ECOPIA™ will provide a NBCCMS effecting an increase in the natural capture and storage of carbon, enabling the control and regulation of $CO_2$ levels in the atmosphere via natural mechanisms. Many of the current nature based solutions have significant uncertainties that largely come about from the practice of engineering the composition of the environment. ECOPIA™ takes a different approach, that of channelling light down to the depths where there are plenty of naturally determined nutrients and seed phytoplankton population. Through simply providing light and nothing more, ECOPIA™ provides no mechanism for a preferential pressure on the naturally determined biodiversity of the light cultured ecosystem, or any external chemical pressure on the solute composition of the seawater itself. It works in concert with the incumbent natural ecosystem.

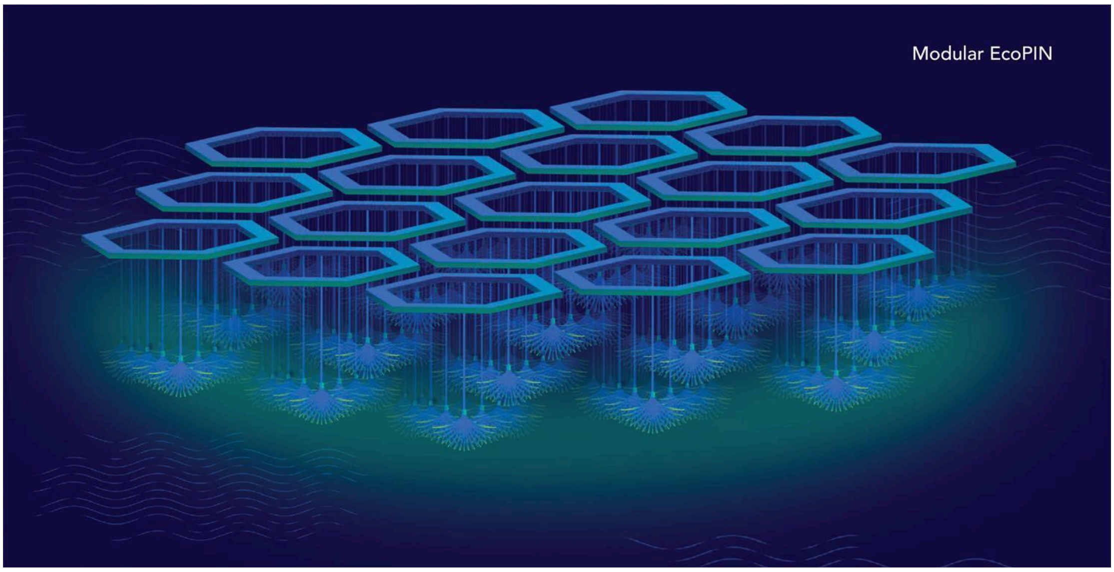


**Figure 1**: An artist's impression of a modular ECOPIN

ECOPIA™ is a modular, scalable solution made up of ECOPINs (Earth Climate Optimisation Productivity Island Nodes) which themselves are modular (**Figure 1**), scalable floating structures. Each ECOPIN will take up approximately 2,000 $km^2$ of ocean surface. The ECOPINs that make up ECOPIA™ will generally be located in the great oligotrophic gyres of the world's oceans. These otherwise minimally productive gyres are growing at a rate of 800,000 $km^2$ per year, at the cost of productive ocean areas. Taking the, perhaps pessimistic but probably realistic, view that the world as a whole can only achieve a static anthropogenic fossil fuels usage by the year 2030, then around 100 ECOPINs will be required; this is derived from the approximately 100 Megatonnes uptake of carbon as atmospheric $CO_2$ to be achieved per ECOPIN per year, or 10 Gigatonnes per year by ECOPIA™ in total. Of course as a scalable system, if greater reductions in fossil fuels usage can be achieved then the size of ECOPIA™ reduces approximately linearly.

## 3. Calculation of CDR

The large sub-tropical open oceans are dominated by the anticyclonic wind driven gyres of the low to mid latitudes (**Stommel, 1948**). These circulations are convergent in the upper ocean and drive permanent deep mixed layers (**Figure 2**). The mixed layers are so deep (100-300 m) that only rare extreme storm events can penetrate to the nutrient rich deep ocean waters; and therefore the surface ocean remains an oligotrophic (nutrient exhausted) 'desert' all year round (**Longhurst, 1988, 2007**; **Morel et al., 2010**), albeit still supporting diverse microbial communities of comparatively small cell size and abundance (**Yin et al., 2013**). Furthermore these enormous, deserts, one seventh (~ 50 million $km^2$) of the whole of the Earth's ocean area (~ 362 million $km^2$), are getting bigger; with high chlorophyll surface waters being replaced by the increase in the surface areas of the oligotrophic gyres, at a rate of 0.8 million $km^2$ per year (**Polovina et al., 2008**; **Signorini et al., 2015**). ECOPIA™ in total only requires 0.2 million $km^2$ of those gyres, just one quarter of the current increase in area per year: but how do we get to this number ?

Ocean Colour data from Earth Observation satellites, for example https://oceancolor.gsfc.nasa.gov/atbd/chlor_a/, and **Figure 2**, are good for the relative contrast and comparison between high and low overall productivity regions of the world's oceans. They clearly show the sub-polar regions as comparatively highly productive with chlorophyll concentrations of around 1 mg $m^{-3}$ as a seasonal or annual mean. However the temporal and spatial averaging belies the true level of productivity at any one point or time. This can only be reliably measured in-situ. The reason for this is that even in the sub-polar regions, the supplies of nutrients to the surface ocean, either through winter mixing or mesoscale (eddy or frontal) upwelling are exhausted by photosynthetic growth in very short timescales (days) and at a biological patchiness space scale (<<1-10 km) (**Mackas et al., 1985**; **Martin, 2003**; **Lévy et al., 2018**; **Robinson et al., 2022**).

In ECOPIA™, however, we provide light to a sub-surface layer, of in practice limitless nutrient supply, that is slowly moving past this geostationary light source; thus providing an ideal and continuous growth environment.

In-situ measurements of sub-polar latitude blooms, whether following over-winter mixing (**Friedland et al., 2016**) or mesoscale eddy stirring processes (**Brown et al., 2003**), typically result in blooms of 5-12 mg $m^{-3}$ chlorophyll concentration, as the nutrient supply is still only sufficient rather than plentiful (**Allen et al., 2005**). A deep chlorophyll maximum may frequently be observed just above the thermocline if it is still within the light penetrating photic zone and chlorophyll concentrations of typically up to 1 mg $m^{-3}$ or more may be maintained here for some time, again due to sufficient vertical mixing across the thermocline, but also low-light adaptation processes within the phytoplankton cellular photo mechanisms (**Cornec et al., 2021**).

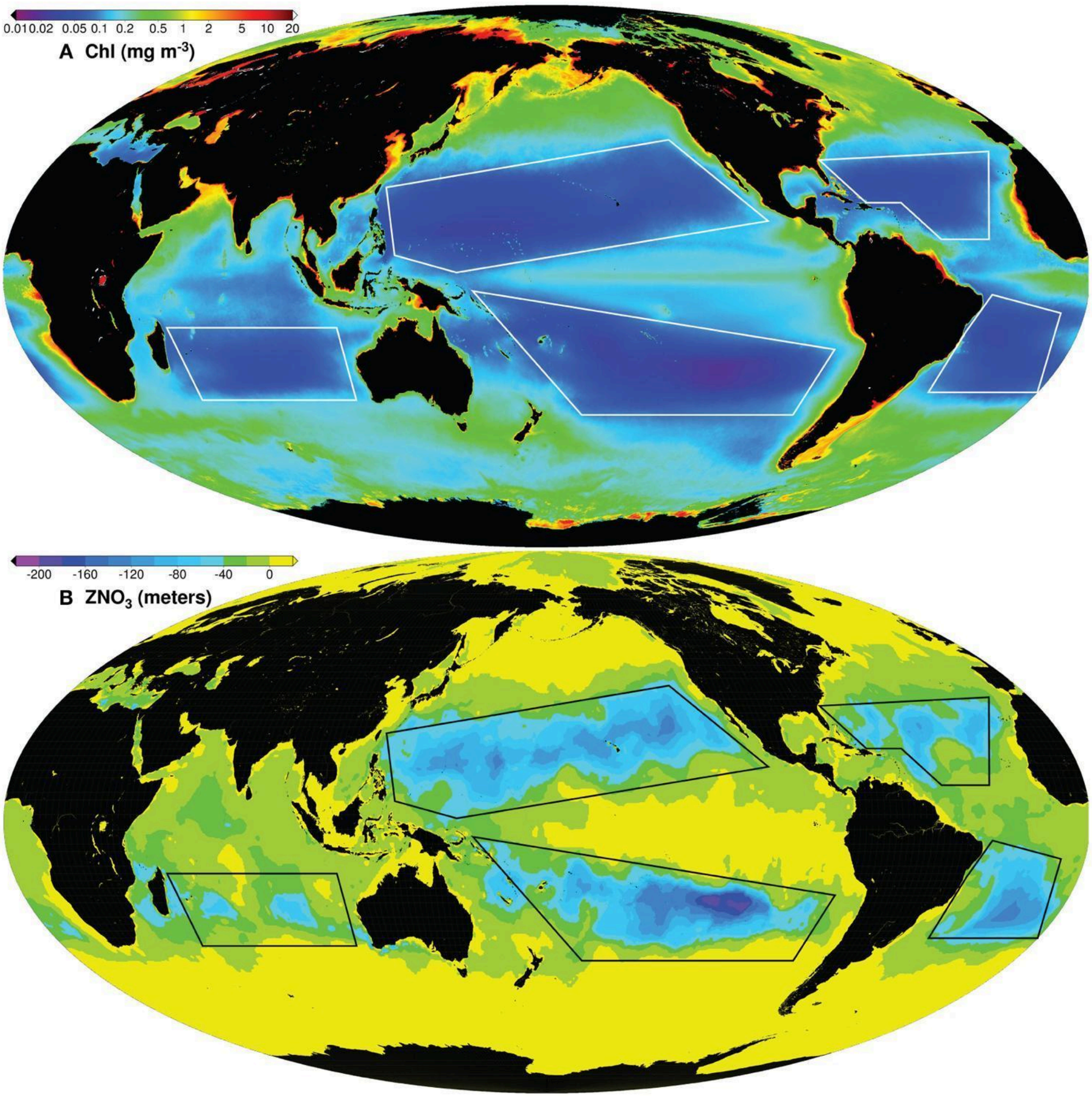


**Figure 2:** Global maps of 9 km MODIS A OCI Chl-a mission composite (A) and the depth of the 0.2 μM ($ZNO_3$) nitrate concentration (B) derived from the World Ocean Atlas monthly climatology. Reproduced from Frontiers, **Signorini et al.** (2015).

Mesocosm experiments, however, where artificial water columns are seeded with phytoplankton and the necessary nutrients for growth, have been shown to produce phytoplankton bloom chlorophyll concentrations of 60 mg $m^{-3}$ or more (**Peperzak et al., 2011**) when a plentiful supply of nutrients is provided. Furthermore a $day^{-1}$ doubling rate can be achieved under these conditions even with modest light supplies of 200 μmole photons $s^{-1}$ $m^{-2}$ ; which corresponds to the typical maximum irradiance phytoplankton are acclimatised to accept in the turbulent surface mixed layer before becoming photo-saturated (**Bouman et al., 2018** ).

In ECOPIA™ we will supply 750-1500 μmole photons $s^{-1}$ $m^{-2}$ of light after allowing for at least 50% propagation loss over the long (100-300 m) light fibre bundles. Daylight surface light levels available for capture at sub-tropical latitudes are ~ 1500-3000 μmole photons $s^{-1}$ $m^{-2}$ (http://www.pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-so lar-insolation). This light will be delivered by a photo-diffuser over a depth range of ~ 20 m or greater and an assumed worst case photo propagation distance, euphotic depth (**Lee et al, 2007**; **Sverdrup, 1953**), of 30 m. Thus we can conservatively assume 30 mg $m^{-3}$ Chlorophyll concentration over a 50 m 'photic' depth at a $day^{-1}$ doubling rate; which equates to 1.5 g $m^{-2}$ $day^{-1}$ chlorophyll growth, or > 500 g $m^{-2}$ $year^{-1}$. Nutrients remain plentiful as a result of the geostationary design of the ECOPINs and the natural currents flowing past at depth, thus preventing any noticeable decrease in nutrient concentrations.

Carbon to Chlorophyll (C:Chl) ratios in marine phytoplankton vary between 10-300 (**Sathyendranath et al., 2009**; **Jakobsen and Markager, 2016**), so assuming a modest C:Chl ratio of 100 gives us a carbon uptake of 50 kg C $m^{-2}$ $year^{-1}$. This equates to ~ 100 Megatonnes of Carbon per ECOPIN per year, or ~ 10 Gigatonnes per year by ECOPIA™ in total (100 ECOPINs). Importantly we have not yet invoked low light adaptation of the phytoplankton photo mechanisms, mentioned above, which will act to significantly increase the volume of the effective photic zone created by each ECOPIN.

Approaching our calculation from the other direction, it is generally considered that approximately 10% of surface ocean primary production is exported below the thermocline (**Siegel et al., 2016**) as detritus and faecal pellets. ECOPIA™ transports light below the thermocline to allow new production to take place below the thermocline where the resulting particulate organic carbon (POC), of detritus and faecal pellets, is by traditional definition already exported. That way it initially makes sense to consider that ECOPIA™ might only require ~ 10% of the area it would require at the surface if nutrients were available. Furthermore, the productive surface ocean is generally only nutrient sufficient, and only for the typically short duration of a bloom as discussed earlier. Whereas below the thermocline, nutrients are plentiful and water is continuously flowing past, so ECOPIA™ provides a continuous growth season. Thus under ECOPIA™ less than 0.06 % of the total ocean surface (~ 0.40 % of the surface area of the oligotrophic gyres) is required to create the 10% increase in oceanic carbon export that is needed to re-balance the Earth carbon cycle.

## 4. Monitoring net CDR

Whilst it is perfectly reasonable to calculate CDR as net exported primary production as we have above in section 3, it is also important to remember that to be an effective 'Climostat' we need removal on at least science and technology development timescales (10-100 years) and preferably multigenerational human timescales (100-1000) years. In other words we need to monitor and show that there are not mechanisms that might create a shorter circuit loop to bring the $CO_2$ back into the atmosphere, and that we can quantify this return flow if there are. This is the most challenging part of any CDR mechanism.

There are four stages to the ECOPIA™ monitoring system that will be expanded upon in the following four sub-sections. These stages are firstly, the continuous monitoring of New Production and therefore $CO_2$ uptake and drawdown. Secondly the frequent and regular integration/assimilation of all monitoring observations into a global coupled biogeochemical model such as MEDUSA2.

Thirdly, scientific cruises targeted by the forecasts of the numerical modeling, to regions of critical interest: and fourthly the observation of atmospheric $CO_2$ concentration reduction.

### *4.1 Routine observational monitoring*

Each full ECOPIN is made up of 19 modules (**Figure 1**), each of which will carry a minimum of three observational stations associated with light carrying conduits. These stations will carry a cluster of instruments at each of four different depths, the surface, the mid-depth between the surface and the light diffusing depth, the light diffusing depth, and 50 metres below the light diffusing depth. The cluster of instruments will include, but not necessarily be limited to, a CTD (conductivity, temperature, pressure) sensor, a sound speed sensor, a microSTAF active fluorescence primary productivity sensor, a passive fluorometer, a solid state nitrate sensor, a particle detector, and sensors for oxygen concentration, $pCO_2$ and pH. In addition water will be regularly pumped from these four depths to the surface for further particle analysis, imaging and flow-cytometry, wet chemistry for pH, $pCO_2$ and total alkalinity and silicate, nitrate/nitrite, phosphate and urea concentrations, and spectrometric studies for $^{13}C/^{12}C$ isotope ratio determination. A further 12 observational stations will be equally spaced around the periphery of each full ECOPIN. At the surface, at all stations, samples will also be taken for determination of Dimethylsulfide (DMS) production, other bio-reactive aerosols, and both nano- and micro- phytoplankton. Any differences between nano- and micro- phytoplankton community between the periphery and interior of an ECOPIN will monitor changes in natural surface production, if any.

Like the ECOPINs these observations will be geostationary and focus primarily on measuring either primary production directly or key indicators of photosynthetic processes, both inputs and products. A secondary focus, notably resulting from the particle analysis, is the direct export of particulate organic carbon (POC) through detritus, and secondary production, through predominantly zooplankton; this includes faecal material and flocculated dead algal material.

Every year each full ECOPIN will be responsible for launching three profiling biogeochemical (BGC) Argo floats and one BGC equipped ocean glider. These will be new vehicles to begin with but as ECOPIA™ builds vehicles will be recovered and re-deployed. As well as supporting the ECOPIA™ routine observational monitoring programme, these vehicles will support and become part of the International Argo Programme, argo.ucsd.edu/, and the International Everyone's Glider Observations (EGO) programme, www.ego-network.org/. Both the floats and the gliders will be equipped with a minimum of a CTD instrument, a passive fluorometer and oxygen concentration, $pCO_2$ and pH sensors. The gliders will also be fitted with nitrate and microSTAF instruments.

The Argo floats will be deployed suitably offshore of the ECOPINs such that they follow the large scale anticyclonic (clockwise in the northern hemisphere and vice-versa) inward spiralling flow of the oligotrophic gyre in which they sit. Argo floats are designed to have a lifespan of around 5 years. This lifespan is expected to enable the floats to at least close on the convergent centre of the gyre, in even the largest, Pacific, gyres; even at a mean drift velocity of only 10 cm $s^{-1}$ this is a lifetime distance of over 18,000 km. The Argo floats can be picked up, where and when convenient, recharged and serviced, and re-deployed. The gliders, equipped with the BGC instruments, will have a typical duration of approximately 6 weeks. At a mean forward speed of 25 cm $s^{-1}$ this gives them a range of around 1,000 km. Therefore the gliders will be piloted around and between ECOPINs where they can be recovered, serviced and re-deployed conveniently.

### *4.2 Model integration and forecasting*

At the core of the ECOPIA™ MRV protocol is the frequent and regular integration/assimilation of all monitoring observations into a global coupled biogeochemical model. This model is likely to be MEDUSA2, projects.noc.ac.uk/medusa/, which has been developed and is operated within the framework of the Nucleus for European Modelling of the Ocean (NEMO) physical model, www.nemo-ocean.eu/. Many of the ECOPIA™ observations may be directly assimilated or used to constrain the MEDUSA2 model components (**Figure 3**). Other observations may be used in concert to deduce further constraint on model parameters.

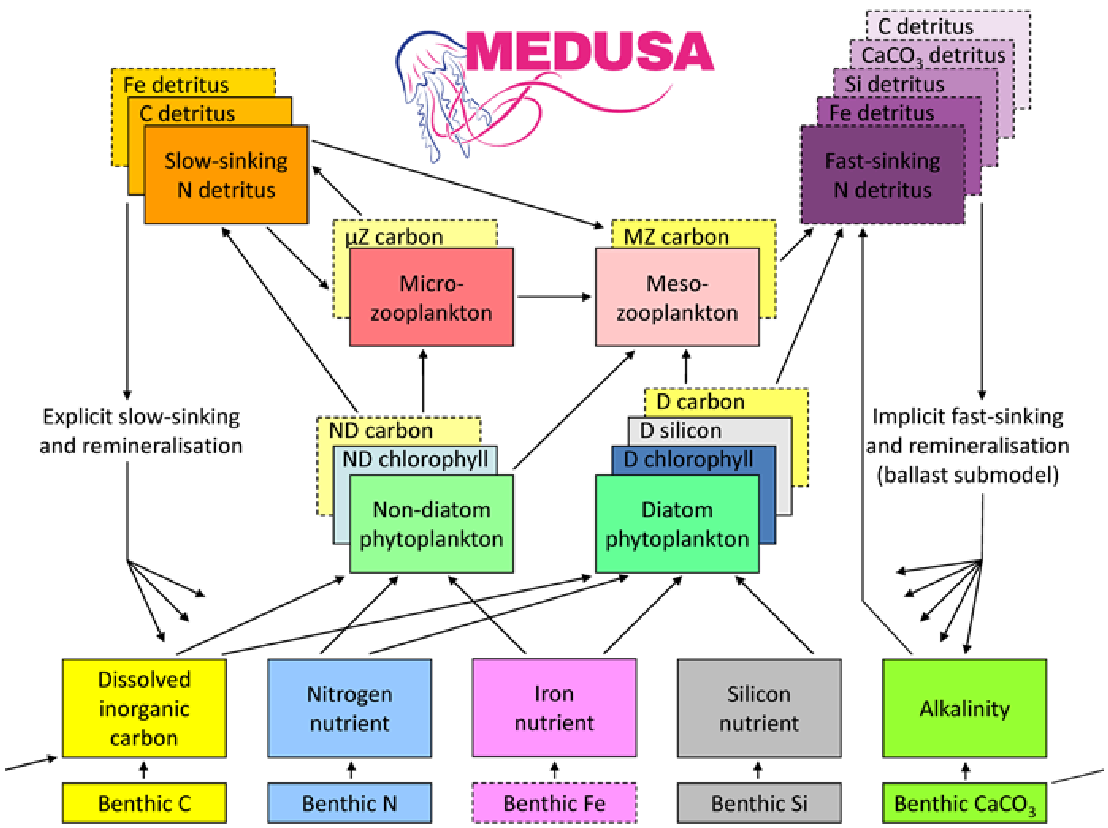


**Figure 3:** Medusa-2.1, from projects.noc.ac.uk/medusa/.

The principal aim of ECOPIA™'s modelling effort is the quantitative determination of "lock-away" of carbon into the deep ocean, and by extension, the identification of any potential pathways of escape. Creating productivity below the permanent thermocline greatly enhances the export potential of new primary production locally. However, even the deep ocean is not quiescent and it is critical that we identify any potential routes to leakage, over a timescale of at least 100 years, through three dimensional ocean circulation patterns and processes (**Baker et al., 2022**).

### *4.3 Targeted scientific experiments*

Where modelling forecasts created from ECOPIA™'s modelling effort and/or independent models or studies outwith ECOPIA™'s comprehensive MRV protocol, indicate any potential routes to upwelling of newly exported carbon from these depths, these will be investigated with significant haste following recognition by ECOPIA™'s independent science advisory board. This will result in scientific expeditions, manned or unmanned, targeted by the forecasts of the numerical modelling, to any regions of critical interest. These expeditions will follow standard principles of Responsive Mode Operational oceanography. A funded call will be placed to invite interested independent and government funded research organisations around the world, but particularly around the ocean basin in question, to become involved in the design and execution of a multi-disciplinary observational campaign to ground-truth the forecast model.

Let us demonstrate an example of responsive mode multi-disciplinary operational oceanography. Uncharacteristically rapid variations in nutrients, particulate organic carbon, or zooplankton biomass are predicted across a developing oceanic frontal or eddying region, in one of the oligotrophic gyres in the numerical model (4.2). These variations are most likely associated with sharp changes in water mass characteristics. Ocean colour satellite images also indicate that the surface waters (0-30 m) are uncharacteristically turbid or even productive in the vicinity of the front but patchiness indicates a significant influence of dynamic physical processes in the region. Further, in general, satellite images also indicate that mesoscale meandering of the front may be at least as pronounced in ocean colour as in infra-red images; suggesting that biological patchiness is dominated by physical processes.

In response, a cosmopolitan vehicle survey region is determined from the satellite images and a regional nested multidisciplinary numerical model is initialised at the beginning of an oceanographic observational campaign whilst the instrument platforms are clustering to begin their surveying. Possible cosmopolitan vehicle surveys are simulated in the regional numerical model output and an objectively optimised campaign survey pattern is derived. A first survey period begins with a mixture of manned and unmanned instrument platforms.

Data from the first survey period are routinely assimilated into the numerical model as quickly as they can be processed and roughly calibrated, minutes to a few hours. The model forecasts are continuously used to choose targeted water and biological sampling stations for the slower key traditional state assessment observations that cannot be made by electronic instrumentation. In addition, the objectively optimised campaign survey patterns continue to be obtained from the model forecasts and both manned and unmanned assets are adaptively managed accordingly during the survey period.

Following completion of the first survey period, a preliminary data analysis will be merged with the latest numerical model forecasts and satellite images to confirm agreement or otherwise with the potential magnitude and pattern of leakage. If there is agreement, i.e. there is a potential source of leakage, then two further survey periods will follow, again following an objectively optimised strategy and adaptive sampling, to improve the quantification of leakage and obtain a confidence level in that value.

If there is disagreement between the original forecast and the preliminary data analysis, i.e. there is little or no evidence of export carbon leakage, then although good news, the model forecasts and the observations will be re-analysed to look for feedbacks to improve forecasting 'skill'. This will lead to better understanding and improvements to the multidisciplinary assimilation of observation data into coupled physical and biogeochemical models.

What is critical here is continuously quantifying the quality of the ECOPIA™ Carbon Offset Credits as well as their quantity (See section 5). Where leakage, as discussed above, is significant enough to damage quantity or quality of Carbon Offset Credits, consideration must be given to the geographical arrangement of ECOPINs in their respective gyres. Repositioning will be modelled and carried out as required.

### *4.4 Observation of atmospheric $CO_2$ reduction*

The objective of ECOPIA™ is the reduction of atmospheric $CO_2$ concentration to the globally agreed level of 350 parts per million (ppm) as quickly as possible; through an operational Earth Climostat to enable our natural regulation of the carbon cycle component of the Earth System. Therefore the fourth and completion component of the ECOPIA™ monitoring programme is focussed on the observation of atmospheric $CO_2$ concentration reduction directly.

ECOPIA™'s most important milestone in its objective is the observation of a reduction in $CO_2$ concentration measurements at the Mauna Loa, Hawaii, atmospheric observatory and other atmospheric observatories around the globe. However we must expect and be prepared for some time delay, before we see this milestone after the start of ECOPIN construction and operation, for a two reasons. Firstly, we expect each full ECOPIN to be responsible for 100 Mega-tonne of carbon drawdown per annum, and therefore, due to the sensitivity of measurement, we may have to build a greater proportion of the total expected, 100 ECOPINs, before a rapid or significant observation of effect is seen in these observatories. Secondly, there will be some time delay regarding the uptake of $CO_2$ through photosynthesis at 200-300 m in ECOPIA™ and the drawdown of atmospheric $CO_2$ through the sea surface; we address this in the following two paragraphs.

Three dimensional advective processes and turbulence are ubiquitous in the oceans; these are the equivalent of stirring in a cup of coffee and speed up the effective mixing timescale by as much as two orders of magnitude from that of pure diffusivity. Recent quantification estimates of coherent three dimensional advection processes (**Allen 2017**; **Frielich et al., 2023**) indicate that they could account for a significant proportion of export to the deep ocean of organic carbon, alongside gravitational sinking and turbulent mixing. And, as early as the mid 1980's we knew that anthropogenic $CO_2$ had made it throughout the whole depth of the North Atlantic ocean oligotrophic subtropical gyre (**Chen, 1987**).

From mid 1990's data (**Sabine et al., 2002**) anthropogenic $CO_2$ had quite clearly reached a depth of over 1500 m in the Indian ocean oligotrophic subtropical gyre. Assuming an exponential growth in anthropogenic $CO_2$ production since the mid 1880's, https://www.climate.gov/media/14596, these studies provide evidence for an equivalent effective diffusion timescale of at least order 100 m/year vertically. Even in the most conservative of the oligotrophic ocean gyres, those in the pacific, where the anthropogenic input is perhaps at the greatest distance from its source, the difference from the 1990's WOCE experiment data and the 2000's CLIVAR experiment data for delta13 ($^{13}C/^{12}C$) $CO_2$ concentrations (**Quay et al., 2017**) indicated an anthropogenic $CO_2$ uptake rate of almost a billion tonnes per year in total, with the largest proportion of this at the subtropical oligotrophic latitudes. At 100 m/year vertical mixing, ECOPIA™, working alongside and assisting the natural biological restoring pump, is expected to have just a 2-3 year lag factor in terms of surface drawdown at the ocean/atmosphere interface.

Of the $C^{13}$ and $C^{12}$ stable isotopes of carbon, the natural photosynthetic mechanisms in plants preferentially take up $CO_2$ containing $C^{12}$ as it is the lighter and smaller molecule to pass through the cellular membranes, and marine phytoplankton are no exception. As a result, a pre-anthropogenic atmosphere has a relatively high $C^{13}/C^{12}$ ratio. However, the anthropogenic mechanisms for the combustion of fossil fuels have no such preference and therefore the atmosphere $C^{13}/C^{12}$ ratio, as measured at atmospheric observatories such as Mauna Loa has been steadily decreasing. Thus the delta13 ($^{13}C/^{12}C$) $CO_2$ concentration is now considered to be the standard measure for observing and identifying anthropogenic $CO_2$ in sea-water samples (**Quay et al., 2017**). Although quite a complicated wet chemistry measurement it will be a standard water sample measurement made on the ECOPINs (section 4.1), and global assessments of delta13 ($^{13}C/^{12}C$) $CO_2$ are one of the baseline science studies underpinning ECOPIA™. As ECOPIA™ grows, and the atmospheric $CO_2$ concentrations begin to reduce, one of the first things that may be seen is a levelling out of the atmospheric delta13 $CO_2$ trend, as the lighter molecules are preferentially stripped out by the additional ECOPIA productivity.

Major earth observing satellite missions are now able to map vertically integrated atmospheric $CO_2$ concentrations at horizontal scales between a few kilometres to 1,000 km depending on the signal level. Using spectrophotometric instruments to examine the reflected sunlight from the earth's surface these satellites are able to detect the characteristic absorption spectrum of different gases in the atmosphere and estimate their concentrations. The current NASA orbiting carbon observatory OCO2, https://ocov2.jpl.nasa.gov/, was launched in 2014 and was followed by OCO3 in 2019. Both of these missions are on-going and look at a colour spectrum of 17,500 colours. They are able to map weak natural variations in vertically integrated atmospheric $CO_2$ concentration at scales around 1000 km, sufficient to monitor significant increased atmospheric $CO_2$ drawdown by ECOPIA™ at oligotrophic gyre scale. Much larger signals, such as plumes from industrial complexes can be mapped at much smaller scales, 10 km or less (**Nassar et al., 2022**). The European Space Agency (ESA) will expand its earth observation capacity with its own CO2M mission launches beginning in 2026. Two and perhaps eventually three satellites will be launched including also near Infra-Red (IR) and short wave IR spectrophotometers. These satellites will have expected pixel sizes of 4 $km^2$. ECOPIA™ will seek to work closely with both NASA and ESA to detect increased natural reductions in atmospheric $CO_2$ concentration at 100-1000 km scale to support and constrain our atmospheric coupled boundary in the model integration and forecasting (section 4.2).

## 5. Conclusion and Discussion

### *5.1 CDR Calculation*

The below calculation summarises how to calculate the net CDR achieved by ECOPIA™ and any given ECOPIN.

$$CDRnet = CDRgross - CDRleak$$

The $CDR_{gross}$ value for a given ECOPIN is taken to be the sum total of the primary productivity, as measured (section 4.1), over a given period of time that is exported below the thermocline. As the primary productivity stimulated by an ECOPIN is produced below the thermocline, unlike the 10% of surface productivity considered to be exported as it moves below the thermocline (**Siegel et al., 2016**), we can consider ECOPIN primary productivity as already exported and therefore $CDR_{gross}$.

The $CDR_{leak}$ value for a given ECOPIN is taken to be that portion of the $CDR_{gross}$ which is shown by an informed global coupled biogeochemical model to leak out of the ocean carbon sink through three dimensional ocean circulation patterns and processes in a timescale less than 100 years (**Baker et al., 2022**).

The $CDR_{net}$ value for a given ECOPIN is calculated as the remainder of $CDR_{gross}$ for that ECOPIN after the modelled $CDR_{leak}$ value for that ECOPIN has been subtracted. This $CDR_{net}$ value is simplistic but represents the fraction of $CDR_{gross}$ that contains the highest quality Carbon Offset Credits. Within $CDR_{leak}$ there will be other fractions of $CDR_{gross}$ , that are Carbon Offset Credits of differing qualities, determined by the timescale of their permanence.

### *5.2 Quality of ECOPIA™ Carbon Offset Credits*

There are 5 things that a high quality carbon offset credit should be able to demonstrate:

1. Additionality
2. Avoidance of overestimation
3. Permanence
4. Exclusive claim to Greenhouse Gas (GHG) reduction
5. Not associated with significant social or environmental harms

We will set out below why Carbon Offset Credits produced by ECOPIA™ are of the highest quality.

#### *5.2.1 Additionality*

Additionality sets out to demonstrate that the carbon offset (CDR) would not have occurred naturally without the activity.

With ECOPIA™, we believe that this is simple to demonstrate as the planned location for the stimulation of primary productivity lacks a vital component for primary productivity without the activity, i.e. light. Without light there is no primary productivity. The primary productivity stimulated by ECOPIA™ takes dissolved inorganic carbon and converts it to organic carbon that is then exported to the deep ocean carbon sinks, CDR. As there is only very minimal microbial surface primary productivity in any given location of the oligotrophic gyres, before an ECOPIN stimulates it at depth, all stimulated primary productivity below the thermocline is additional, and any small changes to background surface microbial production will be monitored (Section 4.1).

#### *5.2.2 Avoidance of overestimation*

Overestimation can occur via a number of mechanisms: Overestimating baseline emissions; Underestimating actual emissions; Failing to account for the indirect effects of a project on GHG emissions (aka "leakage");Forward crediting.

The main route for the avoidance of overestimation is through the creation of, and adherence to, a comprehensive MRV for the CDR solution.

Overestimating baseline emissions is coupled closely to additionality, baseline emissions are the emissions that would have occurred in the absence of demand for offset credits. It is important to evaluate whether or not the solution itself is the baseline, i.e. produces no reduction in emissions (is not additional). The particular location of the ECOPINs (in the Oligotrophic Gyres) and the specific location of the stimulation of the primary productivity (at depth where there is no light), and the additionality of the primary productivity stimulated means that any overestimating via this mechanism is minimised.

Underestimating actual emissions is typically caused by measurement error. It is asserted by this MRV document that any measurements (section 4.1) would be verified by an independent scientific body (or bodies) to ensure correctness. Also given the scale of a single ECOPIN the number of monitoring and measurement devices would allow for cross comparison, highlighting any drift. These measures help ensure that any overestimation by the measurement error is minimised.

ECOPIA™ plans to address the mechanism of failing to account for the indirect effects of a project on GHG emissions (aka "leakage") via the frequent and regular integration/assimilation of all monitoring observations into a global coupled biogeochemical model (section 4.2) such as MEDUSA2 (projects.noc.ac.uk/medusa/). The deep ocean is not quiescent and it is critical that we identify any potential routes to leakage, over a timescale of at least 100 years (**IPCC, 2007**), through three dimensional ocean circulation patterns and processes (**Baker et al., 2022**). The modelling provided by a global coupled biogeochemical model such as MEDUSA2 will provide that identification.

Forward crediting refers to Carbon Offset Credits that may be issued for GHG reductions that a solution expects to achieve in the future. This is, increasingly, a mainstream route of funding that CDR solutions look to capitalise on for funding their infrastructure builds. As part of the MRV, once the CDR solution measurements have been verified by an independent third party, a carbon accountancy firm (such as PwC or KPMG) will verify and issue the Carbon Offset Credits. Any forward crediting that ECOPIA™ receives will be notified to and entered into a ledger by the carbon accountancy firm responsible for issuing ECOPIA™ its Carbon Offset Credits. The impartiality of this carbon accounting firm will ensure no overestimation via future crediting by ECOPIA™.

### *5.2.3 Permanence*

Permanence refers to the period of time that any carbon removed from the atmosphere, by a CDR solution, is 'locked away'.

Standard convention is that carbon locked away for 100 years is considered to be permanently removed from the atmosphere (**IPCC, 2007**). ECOPIA™ plans to demonstrate the permanence of its CDR through the use of a global coupled biogeochemical model (section 4.2) such as MEDUSA2 (projects.noc.ac.uk/medusa/). Any potential routes to leakage, over a timescale of at least 100 years, through three dimensional ocean circulation patterns and processes (**Baker et al., 2022**) would be identified by the model.

The amount of leakage identified by the model will be used to optimise both the permanence, and the number of Carbon Offset Credits that achieve this permanence, to ensure the highest quality possible. This information will be used to locate both the ECOPIN's position within its Oligotrophic Gyre and the depth of its stimulation of the primary productivity beneath the thermocline.

As ECOPIA™ is a global, scalable regulation mechanism for the amount of $CO_2$ in the atmosphere (a 'Climostat'), the requirement for permanent lock away of carbon from the atmosphere is lessened. The degree of permanence that is required is that which allows for ECOPIA™ to reduce to and maintain the level of atmospheric $CO_2$ at the globally agreed level of 350 parts per million (ppm).

### *5.2.4 Exclusive claim to GHG reduction*

Exclusive claim to GHG reduction refers to the fact that no two CDR solutions can lay claim to the same GHG reduction if Carbon Offset Credits are to be issued. This is termed double-counting and has, typically, three methods by which it can occur: double issuance; double use; and double claiming.

The comprehensive monitoring and measurement as laid out in Section 4.1 of the MRV, alongside the location of the ECOPINs within the minimally productive Oligotrophic Gyres of the world's oceans, and the depth at which the stimulation of the primary productivity is taking place means that ECOPIA™ can have exclusive claim to the GHG reduction that it effects, preventing double issuance.

The use of a Carbon Accounting Firm to verify, issue and log the Carbon Offset Credits as well be involved in the sale of any Carbon Offset Credits would prevent the issue of double use.

Double claiming will be addressed through ECOPIA™ signing legal attestations asserting exclusive claims to any credited emission reductions, and agreeing to legally convey such claims to the buyers of Carbon Offset Credits.

### *5.2.5 Not associated with significant social or environmental harms*

For a CDR solution to produce high-quality Carbon Offset Credits, it should not significantly contribute to social and environmental harms.

Many of the current nature based solutions have significant uncertainties that largely come about from the practice of engineering the composition of the environment. ECOPIA™ takes a different approach, that of channelling light down to the depths where there are plenty of naturally determined nutrients and seed phytoplankton population. Through simply providing light and nothing more, ECOPIA™ provides no mechanism for a preferential pressure on the naturally determined biodiversity of the light cultured ecosystem, or any external chemical pressure on the solute composition of the seawater itself. It works in concert with the incumbent natural ecosystem.

### *5.3 Conclusion*

ECOPIA™ can monitor and measure the amount of gross CDR that it achieves through its comprehensive use of Ocean Science and technology.

Through using state of the art global coupled biogeochemical models, such as MEDUSA2, and targeted ocean science experiments, ECOPIA™ will be able to identify and address any leakage of CDR back into the atmosphere. This allows ECOPIA™ to assure as to the permanence of any CDR and the quantity of CDR that achieves that permanence.

By identifying both the gross CDR and the amount of CDR leakage, ECOPIA™ is able to clearly identify the net CDR achieved by the solution.

Additionally through the use of remote earth observing satellite missions, ECOPIA™ will be able to monitor and observe the level of atmospheric $CO_2$

ensuring that it can stay true to its objective of reducing the level of atmospheric $CO_2$ at the globally agreed level of 350 parts per million (ppm).

Carbon Offset Credits issued to ECOPIA™ will be of the highest quality as they will meet all of the 5 criteria for determining high quality Carbon Offset Credits.

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