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Key Points:

- Surfactant would be required to increase wake area enough to reduce temperature significantly
- A 0.2 albedo increase and at least ×1200 lifetime increase of wakes is required
- Additional ships could be used to reduce temperature further and improve coverage of forcing

Supporting Information:

- Figures S1 and S2

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Can increasing albedo of existing ship wakes reduce climate change?

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Abstract Solar radiation management schemes could potentially alleviate the impacts of global warming. One such scheme could be to brighten the surface of the ocean by increasing the albedo and areal extent of bubbles in the wakes of existing shipping. Here we show that ship wake bubble lifetimes would need to be extended from minutes to days, requiring the addition of surfactant, for ship wake area to be increased enough to have a significant forcing. We use a global climate model to simulate brightening the wakes of existing shipping by increasing wake albedo by 0.2 and increasing wake lifetime by ×1440. This yields a global mean radiative forcing of $-0.9 \pm 0.6\,\mathrm{Wm}^{-2}$ ($-1.8 \pm 0.9\,\mathrm{Wm}^{-2}$ in the Northern Hemisphere) and a 0.5°C reduction of global mean surface temperature with greater cooling over land and in the Northern Hemisphere, partially offsetting greenhouse gas warming. Tropical precipitation shifts southward but remains within current variability. The hemispheric forcing asymmetry of this scheme is due to the asymmetry in the distribution of existing shipping. If wake lifetime could reach ~3 months, the global mean radiative forcing could potentially reach $-3\,\mathrm{Wm}^{-2}$. Increasing wake area through increasing bubble lifetime could result in a greater temperature reduction, but regional precipitation would likely deviate further from current climatology as suggested by results from our uniform ocean albedo simulation. Alternatively, additional ships specifically for the purpose of geoengineering could be used to produce a larger and more hemispherically symmetrical forcing.

1. Introduction

It is very likely that global warming will exceed 2°C by the end of the century [*Peters et al.*, 2013] unless the level of mitigation by developed nations is increased dramatically and immediately. Reducing the solar radiation absorbed by the Earth could lessen the impacts of global warming. The most studied solar radiation management (SRM) schemes propose reducing absorbed solar radiation by reflecting more sunlight using mirrors in space, with stratospheric aerosols (e.g., stratospheric injection of SO_2), or by making marine clouds more reflective (e.g., injection of sea salt into the marine boundary layer) [*Budyko*, 1977; *Crutzen*, 2006; *Boucher et al.*, 2013; *NAS Report*, 2015]. SRM schemes simulated in climate models are capable of counteracting significant greenhouse gas warming but compared to the preindustrial climate tend to slightly cool the tropics too much and the high latitudes too little [*Kravitz et al.*, 2013a; *Niemeier et al.*, 2013; *Yu et al.*, 2015] and reduce global precipitation too much with shifts in regional patterns [*Jones et al.*, 2010; *Bala et al.*, 2011; *Kravitz et al.*, 2013a; *Niemeier et al.*, 2013; *Tilmes et al.*, 2013; *Yu et al.*, 2015]. Stratospheric aerosol injection is also expected to cause stratospheric ozone loss [*Tilmes et al.*, 2008].

Low-power consumption technologies for generating microbubbles [*Zimmerman et al.*, 2008] could potentially be used to brighten the ocean surface for geoengineering purposes. Naturally occurring bubbles in the near-surface sea water have radii of the order of 10–100 μm and volume concentrations of 10^{-6} to 10^{-7} [*Seitz*, 2011]. The smaller the microbubbles or the larger the volume of air in the water (i.e., a much larger number of microbubbles of the same size), the greater the albedo. Artificial microbubbles with a radius of 1 μm, at a volume concentration of 10^{-5}, could increase the albedo of open sea by 0.2, although this effect is reduced with increasing chlorophyll concentrations [*Seitz*, 2011]. Stable foams in still sea water, consisting of ~1 mm bubbles, have been found to have albedos of at least 0.5 in the absence of chlorophyll [*Aziz et al.*, 2014]. In practice one might have to compensate for the presence of chlorophyll by generating greater volume concentrations of bubbles. Increasing the lifetime of bubbles in ship wakes would increase the areal extent of the wake so could also be used to brighten the ocean surface. Microbubble lifetimes in sea water are strongly dependent on the amount of natural surfactant (surface-active carbohydrates, proteins, and lipids often derived from phytoplankton) and amphiphilic nanoparticles which help stabilize microbubbles. There are few measurements of microbubble lifetimes in seawater from different ocean locations, but it is unlikely that lifetimes are longer than the order of a few minutes [*Johnson and Cooke*, 1981; *Lozano et al*., 2007]. Additional surfactant has been shown to extend bubble lifetimes to a year in fresh water [*Dressaire et al*., 2008] and to produce long-lasting ($>$3 months) foams in sea water in the laboratory [*Aziz et al*., 2014]. However, wave action and turbulent mixing in the open ocean would likely burst these bubbles and break up these foams more rapidly as well as mixing bubbles lower down in the water where they would be less effective. The effect from turbulent mixing would clearly be regionally and seasonally dependent [*Fu et al*., 2010]. Naturally occurring surfactant concentration and therefore the amount of any additional surfactant required are also regionally and seasonally dependent. *Seitz* [2011] showed using the CAM 3.1 global circulation model (an atmosphere model coupled to a slab ocean model) that by increasing the ocean albedo uniformly by 0.05, the equilibrium surface temperature was reduced by 2.7°C, i.e., similar to offsetting the warming from a doubling of CO_2. However, the precipitation response was not presented. *Gatebe et al*. [2011] estimated the top of atmosphere (TOA) radiative forcing produced by the wakes of existing large ocean going vessels to be -1.4×10^{-4} Wm^{-2}. However, existing ships, which cover around 16,000 km^2 of ocean, are not optimized to produce small, long-lasting microbubbles; their wake lifetimes are of the order of minutes and wake albedo gains of the order of 0.02 [*Gatebe et al*., 2011].

In this study we assess whether increasing the albedo and areal extent of current ship wakes could reduce 21st century climate change in terms of surface temperature and precipitation. First, we estimate the minimum increase in albedo and lifetime of the bubbles required to detect a significant and detectable change in global mean surface temperature. We then present results from a climate model simulation using the HadGEM2-CCS ocean-atmosphere coupled climate model implemented with an albedo increase in current shipping lanes. The climate model includes no representation of potential changes to air/sea gas exchanges caused by the microbubbles or bubble bursting or by the presence of added surfactant which is known to reduce gas exchange [*Salter et al*., 2011]. Ship wakes are far more abundant in the Northern Hemisphere so we do not expect them to provide an ideal forcing pattern to counteract greenhouse gas forcing. Therefore, we also perform a simulation with a uniform ocean albedo increase over all open oceans (although still hemispherically asymmetric). We assess the capability of geoengineering to bring the climate back to the modeled 1986–2005 temperature and precipitation climatology. Note that we only have one ensemble member of each simulation and therefore detailed regional responses are less robust than large scale responses.

There is very little literature on how bubble lifetime varies with different concentrations of surfactant or with different types of surfactant in sea water. Neither is it known what the effects of turbulent mixing and hence the lifetime of the bubbles near the surface would be. Therefore, assessment of the amount or type of surfactant required is beyond the scope of this study, as is the assessment of undesirable side effects from the addition of surfactant.

2. Climate Model Description

We use the UK Met Office HadGEM2-CCS coupled ocean-atmosphere general circulation model [*Martin et al*., 2011; *Hardiman et al*., 2012], which includes processes for sea ice, ocean geochemistry and the terrestrial carbon cycle, as well as interactive schemes for various aerosol species. The model atmosphere has 60 vertical levels extending to 84.5 km altitude, which provides enhanced representation of stratospheric dynamics and radiation, and a horizontal resolution of 1.25° latitude by 1.875° longitude. The ocean model has 40 vertical levels, a latitude resolution of 1° between the poles and 30°N/S increasing to 1/3° at the equator and a 1° longitude resolution. The ocean ecosystem model, diatHadOCC, models biological production of phytoplankton (diatoms and other phytoplankton), zooplankton, and detritus. Primary production rate is dependent on the availability of nutrients (nitrogen, silicate, and iron), the shortwave radiation, and temperature.

3. Estimating Surface Shortwave Radiative Forcing of Ship Wake Geoengineering

First, we estimate the instantaneous surface shortwave radiative forcing as a function of ship wake albedo and lifetime of the bubbles within the upper few meters of water, hereafter referred to as near-surface lifetime. We estimate the current average number of ships in each grid cell at any time of the year by calculating the fraction of ocean going ships in each grid cell from the 2008 EDGAR CO_2 emissions data [*Eyring et al*., 2005] for international and domestic shipping (v4.2, 1A3d) and multiplying by the number of merchant ships at sea at any time (32,331 ± 7930) as used by *Gatebe et al*. [2011] (supporting information Figure S1). The most recent year available is 2008. We do not differentiate between different types of ships. The data are extracted on a 0.1 × 0.1° grid and interpolated on to our climate model grid. Emissions data over inland water are omitted. We base the current area of each ship wake on the average measured by *Gatebe et al.* [2011] (0.5 km^2). We calculate the area fraction covered by wake in each grid cell f as

$$f = n\frac{A_s}{A}\frac{L}{L_c}, \tag{1}$$

where n is the number of ships in the grid cell, A_s is the current area of a ship wake (0.5 km^2), A is the total area of the grid cell, L is the extended near-surface lifetime of bubbles in the wake, L_c is the current near-surface lifetime of bubbles in the wake, and therefore, L/L_c is the near-surface lifetime increase factor. We limit f to be no more than 1 to handle potential overlap of wakes within a grid cell. We calculate the instantaneous surface shortwave radiative forcing (F) in each grid cell from the wakes of these ships as a function of near-surface lifetime and albedo increase:

$$F = -If\alpha_s = -In\frac{A_s}{A}\frac{L}{L_c}\alpha_s, \tag{2}$$

where I is the mean downward surface shortwave flux as determined from years 2020 to 2029 of our RCP4.5 simulation (see section 4) and α_s is the albedo increase of the wake relative to the albedo of open ocean (0.05–0.08 without geoengineering). To estimate the actual near-surface lifetime required of the wakes we need the current near-surface lifetime. Cargo ships are 30–50 m wide and the wake spreads out astern. Assuming a visible wake width of 50–100 m, a length of 5 km–10 km, and the speed of the ship 40 km/h (~22 knots), we estimate existing wakes last 7–15 min. Note that this is a little longer than measured lifetimes of microbubbles in sea water possibly due to propeller action enhancing sea surface microlayer concentrations of natural surfactant such as that from seaweed and phytoplankton through bubble scavenging.

4. Climate Model Simulations and Analysis

We simulate the climate from 1860 to 2069 using historical natural and anthropogenic forcings for the period 1860–2005 and thereafter using greenhouse gas and aerosol concentrations from the partially mitigated climate change scenario, RCP4.5 (the Representative Concentration Pathway that produces a forcing of 4.5 Wm^{-2} by 2100) [*Moss et al.*, 2010]. We apply ocean albedo geoengineering on top of this RCP4.5 scenario from 2020 to 2069, following the G4 simulation style of the Geoengineering Model Intercomparison Project [*Kravitz et al.*, 2011]. We assume that society would attempt some mitigation before embarking on a global geoengineering scheme and therefore use RCP4.5 rather than RCP8.5, although we do not believe our results would be very different had we used an alternative scenario. The difference in global mean temperature between the high emissions scenario, RCP8.5, and the RCP4.5 scenario is barely significant up to 2040 and is about 1°C by 2070 in our model. The state dependence of climate response to a given albedo change is unlikely to be large within this range of climates. We simulate an increase in albedo in current shipping lanes by adding the ocean albedo increase $f.\alpha_s$ (equation (2)) calculated for a near-surface lifetime increase factor of ×1440 (i.e., minutes to days) and $\alpha_s = 0.2$, resulting in a total of 19.7 million km^2 of ocean (5.5% of global ocean) covered by wakes. Note this applies to open ocean only. Hereafter we refer to this simulation as SHIPWAKE. We also compare SHIPWAKE to the results of a simulation with a 0.03 uniform ocean albedo increase over all open oceans (hereafter UNIFORM) also applied on top of RCP4.5. We chose to apply a 0.03 albedo enhancement rather than the 0.05 used by *Seitz* [2011] because this level of geoengineering met our goal of returning global mean temperature to the 1986–2005 climatology. UNIFORM has a larger forcing and response from which it is easier to determine causes of regional responses.

We estimate effective radiative forcing due to the geoengineering using the regression method of *Gregory et al.* [2004]. We regress global mean TOA radiative flux anomalies (geoengineering—RCP4.5) against global mean surface air temperature anomalies using the first 10 years of data for SHIPWAKE and the first 20 years of data for UNIFORM, i.e., during the time that the temperature change due to geoengineering is changing. This regression method is also applied to hemispheric means and land and sea means to estimate hemispheric mean and land and sea mean forcing.

We compare surface air temperature and precipitation responses for SHIPWAKE and UNIFORM to the non-geoengineered simulation, RCP4.5 for the 2040–2059 period. This period was chosen because by this time geoengineering has had its full impact (Figure 3). We also compare RCP4.5 to the 1986–2005 annual mean

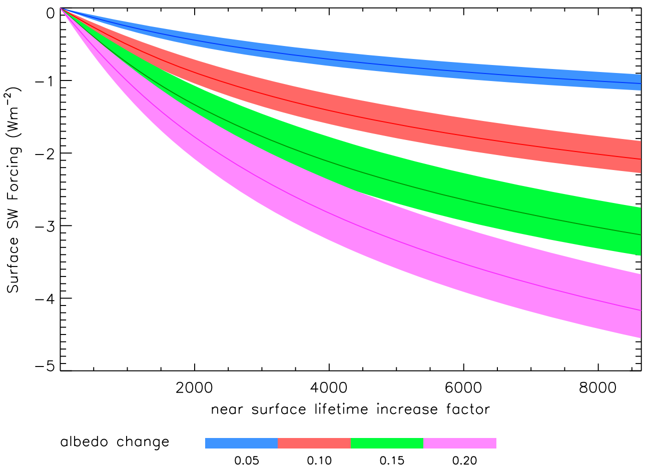

Figure 1. Global mean instantaneous surface shortwave forcing as a function of near-surface lifetime increase for different ship wake albedo increases (0.05 to 0.2 shown in different colors) assuming 32,331 ships. Shading shows the forcing range based on the likely range of the number of ships (24,400–40,261).

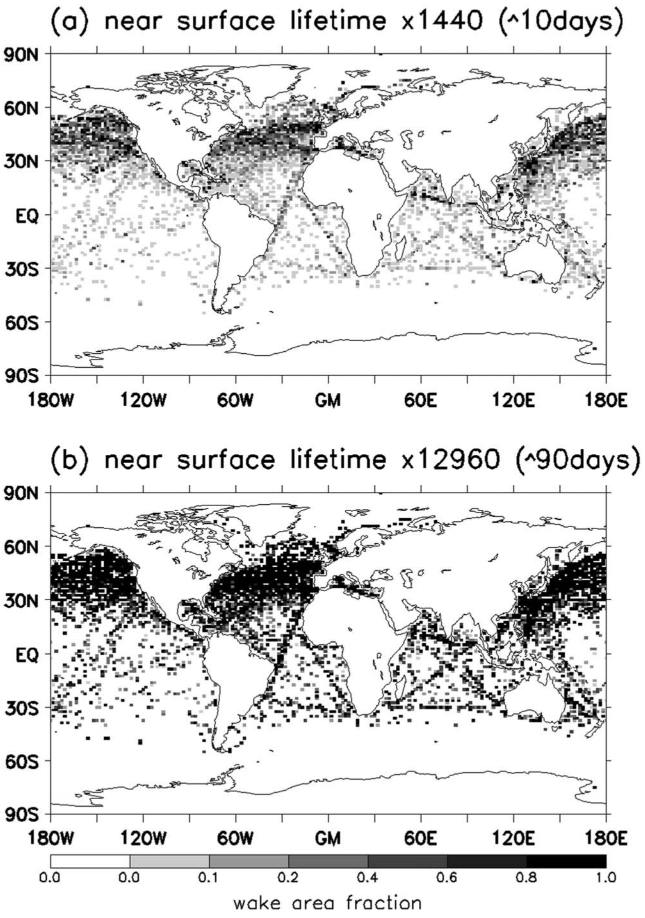

Figure 2. Wake area fraction in each grid box (at climate model resolution) for (a) near-surface lifetime increase of ×1440 and (b) near-surface lifetime increase of ×12,960.

climatology. To determine significance of our results we use standard deviations determined from a 500 year preindustrial control simulation following *Collins et al.* [2013]. Standard deviations of annual means are used to compare against annual mean time series and standard deviations of 20 year means are used to compare the difference between 20 year mean periods. This is the accepted practice of the Intergovernmental Panel on Climate Change. The internal variability was multiplied by $\sqrt{2}$ when comparing to the difference between two simulations because we are testing the significance of the difference between two means.

5. Results

Surface shortwave radiative forcing as a function of the albedo increase and near-surface lifetime increase (Figure 1) shows the radiative forcing from ship wakes could potentially be increased by at least 4 orders of magnitude (i.e., up to 4 Wm^{-2}). The relationship with near-surface lifetime is nonlinear because as near-surface lifetime increases wakes in some grid boxes start to overlap making further near-surface lifetime increases less effective. For a near-surface lifetime increase of ×1440 (~10 day lifetime) 5% of grid cells with ships were totally covered in wake, whereas for a near-surface lifetime increase of ×12,960 (~3 months lifetime) 54% of grid cells with ships were totally covered in wake (Figure 2). In practice there would clearly be no point in adding more surfactant to increase near-surface lifetime further in regions which are already totally covered in wake. We found TOA net radiative forcing, which includes masking by clouds and rapid adjustments in the atmosphere, to be ~0.6 times this surface shortwave forcing. The interannual variability in our surface shortwave radiation (determined from our RCP4.5 simulation) is $\sigma = 0.4\ \mathrm{Wm}^{-2}$. Therefore, we expect a surface forcing

Table 1. Top of Atmosphere Effective Radiative Forcing Due To Geoengineering (the Error Given is 2 Times the Standard Error From the Regressions)

Forcing (Wm^{-2})	SHIPWAKE	UNIFORM
Global		
Net	−0.9 ± 0.6	−2.2 ± 0.6
SW	−1.0 ± 0.4	−2.2 ± 0.6
LW	0.1 ± 0.3	−0.06 ± 0.2
NH		
Net	−1.8 ± 0.9	−1.5 ± 0.7
SW	−1.6 ± 0.8	−1.8 ± 0.7
LW	−0.2 ± 1.2	0.3 ± 0.9
SH		
Net	0.2 ± 0.4	−2.9 ± 0.7
SW	−0.4 ± 0.5	−3.0 ± 1.0
LW	0.6 ± 0.4	0.2 ± 0.9
Land		
Net	−0.04 ± 0.5	0.5 ± 0.6
SW	−0.03 ± 0.5	0.2 ± 0.5
LW	−0.01 ± 0.6	0.3 ± 0.6
Sea		
Net	−1.2 ± 0.6	−3.3 ± 0.6
SW	−1.3 ± 0.6	−3.1 ± 0.7
LW	0.1 ± 0.3	−0.2 ± 0.2

of ~1 Wm^{-2} would be required to yield a significant ($>2\sigma$) signal-to-noise ratio in the global annual mean temperature response, i.e., a near-surface lifetime increase of at least ×1200 with an albedo increase of 0.2. We estimate current wakes last for 7–15 min, suggesting near-surface lifetime would have to increase to at least 6–13 days. This would require the addition of surfactant.

We estimate the effective TOA radiative forcing for SHIPWAKE to be −0.9 ± 0.6 Wm^{-2}, and this comes largely from the Northern Hemisphere (NH) because of the larger number of ships in this hemisphere, with the Southern Hemisphere (SH) having a small positive, although insignificant, forcing likely caused by rapid adjustments in cloud and water vapor (the longwave forcing component was significantly positive) (see Table 1). The forcing is largely over the ocean where the intervention was applied. SHIPWAKE forcing is just less than half that of UNIFORM which has a larger contribution from the SH oceans (see Table 1). If near-surface lifetime could be increased ×12,960 (~3 months lifetime), the TOA radiative forcing would be of the order of −3 Wm^{-2}.

For SHIPWAKE and UNIFORM, annual mean temperature and precipitation decrease over the first 10 to 20 years and thereafter they track the linear trend of RCP4.5 (Figure 3). Temperature change over land is greater than that over sea, because of differing lapse rates over land and sea and the nonlinear dependence

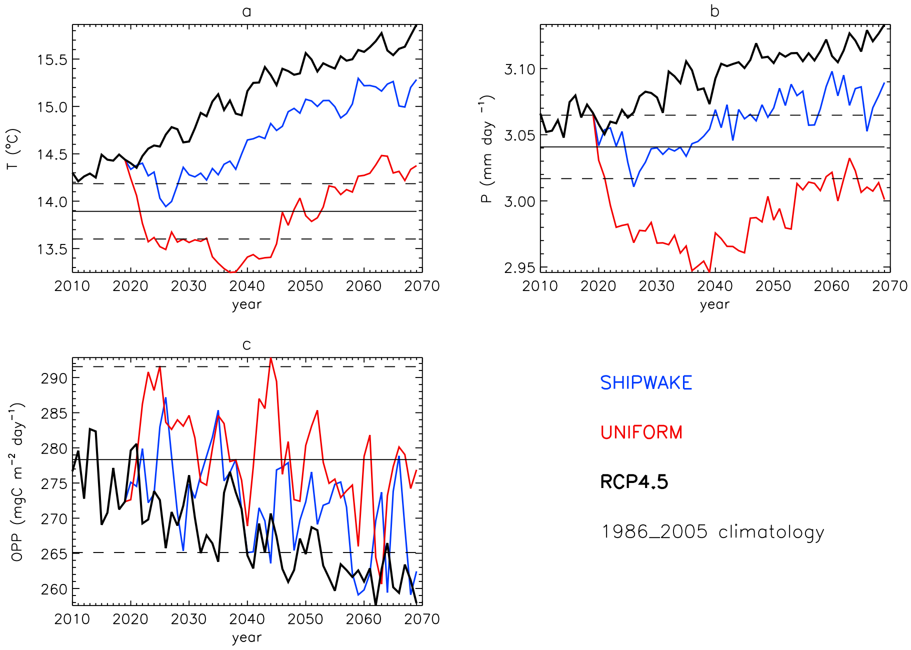

Figure 3. Global mean time series of (a) surface air temperature, (b) precipitation, and (c) ocean primary productivity for the three simulations. The horizontal black line shows the 1986–2005 climatology with the dashed horizontal lines showing ±2 standard deviations of annual means.

Table 2. The 2040–2059 Annual Mean Changes in Surface Air Temperature (ΔT), Precipitation (ΔP), Ocean Primary Productivity (ΔOPP), and Arctic Sea Ice Area (ΔA) for RCP4.5 Minus 1986–2005 Climatology and Geoengineering Minus RCP4.5[a]

	RCP4.5 Minus Climatology	SHIPWAKE Minus RCP4.5	UNIFORM Minus RCP4.5	Climatological Mean
ΔT (°C)				
Global	1.5	−0.5	−1.6	13.9
NH	1.9	−0.9	−1.9	13.8
SH	1.1	−0.2	−1.3	14.0
Land	2.1	−0.8	−2.0	8.0
Sea	1.2	−0.5	−1.4	16.2
ΔP (mm day^{-1})				
Global	0.07	−0.04	−0.12	3.04
NH	0.11	−0.15	−0.07	2.96
SH	0.03	0.07	−0.16	3.13
Land	0.07	−0.002	0.01	2.10
Sea	0.07	−0.06	−0.17	3.42
ΔOPP (mg m^{-2} day^{-1})	−13.8	6.0	13.9	278.3
ΔA (million km^2)	−2.48	0.78	2.52	11.2

[a] The rightmost column gives the 1986–2005 climatological mean absolute values as a reference.

of water vapor concentration on temperature [*Bala et al.*, 2011]. The different heat capacities of land and sea may also play a part. This can be seen for RCP4.5 compared to climatology where the forcing is likely to be similar over land and sea, and for both SHIPWAKE and UNIFORM compared to RCP4.5 despite the forcing being over the sea (Table 2). Global mean precipitation decreases compared to RCP4.5 for both SHIPWAKE and UNIFORM due to decreased radiative cooling of the atmosphere balanced by a decrease in latent heat flux and therefore decreased atmospheric moisture availability [*Kravitz et al.*, 2013a; *Niemeier et al.*, 2013].

SHIPWAKE partially offsets the temperature response of RCP4.5 compared to 1986–2005 climatology with the NH to SH temperature change (geoengineering minus RCP4.5) ratio being much larger than that for RCP4.5 (Table 2). The land to sea temperature change ratio is only slightly less than that for RCP4.5 (Table 2) due to the forcing being predominantly in the NH where most of the land resides. Although much of the land temperature is significantly cooler than RCP4.5 (Figure 4c), it remains more than 2 standard deviations from climatology (supporting information Figure S2a). Precipitation in SHIPWAKE decreases in the NH and increases in the SH and decreases more over sea than land (Table 2). In contrast, precipitation increases equally over sea and land under RCP4.5. Tropical precipitation shifts southward for SHIPWAKE, but for much of the globe precipitation changes from RCP4.5 are insignificant (Figure 4d).

UNIFORM offsets the temperature response of RCP4.5 globally, hemispherically, and over land and sea, although the land to sea temperature change ratio is less than that for RCP4.5 (Table 2). The decrease in precipitation is greater than the increase under RCP4.5, especially in the SH (Table 2) because tropical precipitation shifts northward. Changes are greater over sea than land. Similar responses were found in the G1ocean-albedo simulation of *Kravitz et al.* [2013b] where albedo was increased by a fixed scaling factor rather than by a fixed amount. Although UNIFORM is more effective at bringing the temperature back to the climatology, it cools South Africa (Figures 4e and S2c) such that the tip of South Africa is colder than climatology and increases precipitation in Africa while decreasing precipitation in parts of Eurasia (Figures 4f and S2d) compared to both RCP4.5 and climatology, taking precipitation in the SH and over the global ocean further from climatology than RCP4.5. We find significant increased upward motion in the atmosphere over much of Africa and South America and increased downward motion over parts of the Pacific, Atlantic and Indian Oceans, a pattern very similar to the precipitation change and induced by the forcing over ocean [*Bala et al.*, 2011]. The UNIFORM simulation leaves precipitation significantly further from climatology than does SHIPWAKE (supporting information Figure S2d).

For both SHIPWAKE and UNIFORM the meridional shifts in tropical precipitation were found to be caused by changes to the Hadley cell with increased upward motion compared to RCP4.5 in the hemisphere with the least negative forcing and vice versa in line with *Haywood et al.* [2013].

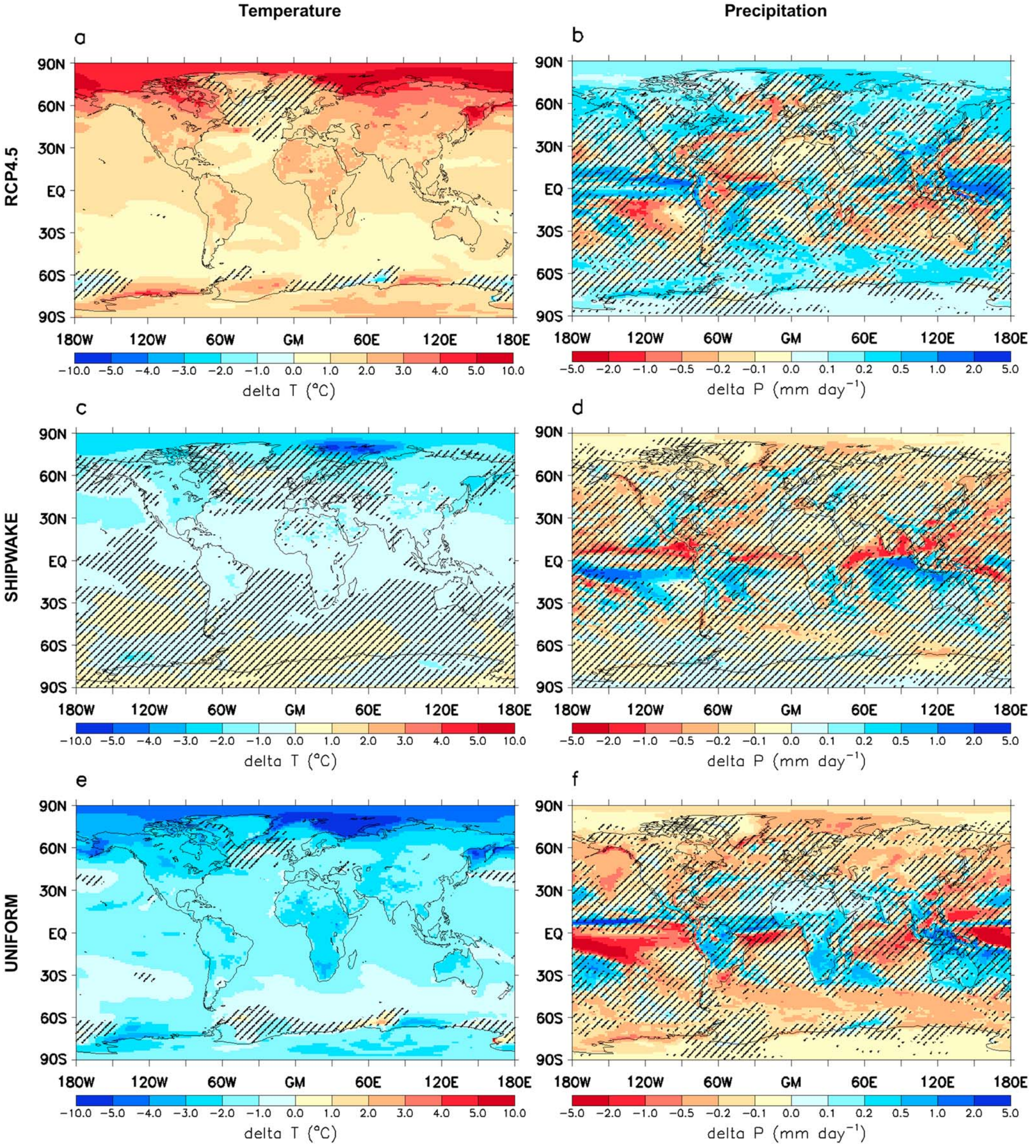

Figure 4. The 2040–2059 mean changes in (a, c, and e) surface air temperature, and (b, d, and f) precipitation for RCP4.5 compared to 1986–2005 climatology (Figures 4a and 4b), SHIPWAKE geoengineering compared to RCP4.5 (Figures 4c and 4d) and UNIFORM geoengineering compared to RCP4.5 (Figures 4e and 4f). Note that the color scale is logarithmic. Hatching shows regions where changes are not significant at the 5% significance level, i.e., where SHIPWAKE/UNIFORM are indistinguishable from RCP4.5 and where RCP4.5 is indistinguishable from 1986 to 2005 climatology.

Evans et al. [2010] highlighted the concern that ocean albedo increases could negatively impact marine ecosystems due to reduced shortwave radiation penetrating the surface of the ocean. We find no clear correlation between the patterns of change in net downward shortwave radiation at the surface and the patterns of change in ocean primary productivity (OPP), particularly in the tropics and midlatitudes, suggesting shortwave radiation is not a limiting factor to OPP in most of the oceans (Figure 5). There is a positive correlation in the Barents Sea, off the south east coast of Russia, and regions close to the Antarctic coast for both SHIPWAKE and UNIFORM where OPP decreases relative to RCP4.5. However, it is only in the Barents Sea in UNIFORM and in a reduced area off the south east coast of Russia for SHIPWAKE and UNIFORM that the change in OPP compared to climatology is also negative. The effect in the Barents Sea for UNIFORM is likely due to increased Arctic sea ice in this region reflecting more sunlight. For both SHIPWAKE and UNIFORM there is a small although insignificant increase in OPP globally (Figure 3c). There are regions of increased and regions of decreased OPP compared to RCP4.5, although for SHIPWAKE they

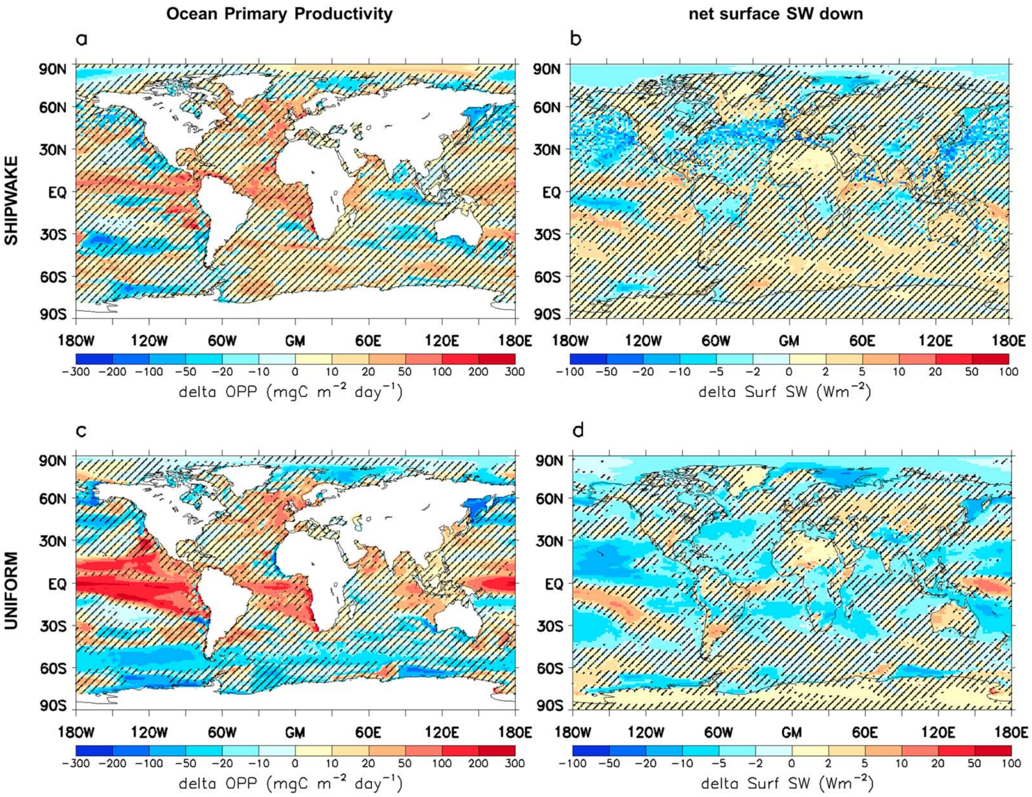

Figure 5. The 2040–2059 mean changes in (a, c) ocean primary productivity and (b, d) net downward surface shortwave flux for SHIPWAKE geoengineering compared to RCP4.5 (Figures 5a and 5b) and UNIFORM geoengineering compared to RCP4.5 (Figures 5c and 5d). Note that the color scale is logarithmic. Hatching shows regions where changes are not significant at the 5% significance level.

are mostly insignificant. The reduced OPP just north of 60°S in the Southern Ocean in UNIFORM is not correlated with changes in shortwave radiation. Our simplified modeling approach is unlikely to include all the effects on OPP which are beyond the scope of this study. In particular changes in air/sea gas exchange due to bubbles or surfactant were not modeled and may affect ecosystems. Also surfactants may be microbially and photochemically processed with undesirable impacts on ecosystems.

6. Discussion and Conclusion

Although our results come from a single climate model, our UNIFORM results were similar to the G1ocean-albedo simulation of *Kravitz et al*. [2013b] which uses a different model, suggesting our large scale results are not highly model dependent. Our results show that increasing albedo and areal extent of ship wakes based on year 2008 shipping could have a significant effect on global mean surface air temperature, providing the area of a ship wake could be increased more than 3 orders of magnitude ($> \times 1200$). This would require the addition of surfactant to increase near-surface lifetime to ~10 days. *Dressaire et al*. [2008] and *Aziz et al*. [2014] have shown that bubble lifetimes can be extended to at least several months but neither study assessed how concentration affects bubble lifetime in open sea where turbulent mixing affects how long the bubbles remain near the surface. Further study is required to determine the ideal concentration and type of surfactant to stabilize microbubbles for the time required within shipping lanes. The amount of surfactant to be added by each ship would depend on the amount of surfactant already present in the water from previous ships which would depend on the lifetime of the surfactant in open sea and the frequency of shipping. It would also depend on the extent of turbulent mixing. The surfactant would clearly need to be environmentally benign for one to be legally allowed to add such a chemical to the oceans.

We find that our SHIPWAKE simulation can also partially restore Arctic sea ice (Table 2) and has impacts on precipitation and OPP that are no worse than those due to climate change. Our simulation did not model the impacts on OPP due to changes in air/sea gas exchange caused by the bubbles and surfactant nor the presence of surfactant. Like all SRM schemes, it does not address ocean acidification and would need to be maintained at ever increasing levels to counteract ongoing anthropogenic climate change. There has been a fourfold increase of ocean going traffic between the early 1990s and the present [*Tournadre*, 2014] suggesting shipping is likely to continue increasing in the near future, potentially providing a greater cooling than in our simulation. Microbubble lifetime could also be increased by addition of more surfactant providing a greater forcing, although the relationship between surfactant concentration and microbubble lifetime and near-surface lifetime is unknown. Ship wakes do not provide the optimum pattern of forcing to counteract climate change due to the greater abundance of ships in the NH. A larger and more uniform radiative forcing could be produced by deploying extra ships with microbubble generators in the SH oceans. Although our UNIFORM simulation was effective at returning temperature to recent climatology and fully restored the annual mean Arctic sea ice area (Table 2), it is unlikely that one would want to produce a uniform albedo enhancement across all oceans given the larger tropical precipitation shifts found in UNIFORM (Figure 4f), caused by the larger radiative forcing involved. Shifts in tropical precipitation are a common issue of SRM schemes [*Jones et al*., 2010; *Bala et al*., 2011; *Kravitz et al*., 2013a; *Niemeier et al*., 2013; *Tilmes et al*., 2013; *Haywood et al*., 2013; *Yu et al*., 2015], but using microbubble generators on ships specifically for the purpose of ocean albedo geoengineering provides a flexible way to generate radiative forcing patterns. Further study is required to determine the best pattern of radiative forcing to achieve greatest effectiveness of surface temperature reduction with least precipitation side effects. We do not propose that full control of precipitation changes would be possible merely that meridional shifts could be reduced through careful balancing of the forcing in each hemisphere.

The application of microbubbles to improve fuel efficiency in the shipping industry [*Kawabuchi et al*., 2011; *Kumagai et al*., 2015] has shown it is possible to attach microbubble generation technology to ships. These air lubrication systems currently use larger microbubbles than would be used for geoengineering. They also require the microbubbles to be touching the hull, whereas for geoengineering the microbubbles need to have longer lifetimes and be spread over the ocean surface. Optimizing these different requirements into a single system could provide a geoengineering scheme that also reduces CO_2 emissions (i.e., reduces the positive CO_2 forcing) and benefits the shipping industry by reducing fuel costs. Ships also emit soot and SO_2 which can brighten clouds and produce ship tracks. Reducing fuel use would also reduce these emissions and the relatively small negative radiative forcing from ship tracks (-4 to $-6 \times 10^{-4}\,\mathrm{W m^{-2}}$) [*Schreier et al*., 2007].

Microbubbles on the surface of the ocean can greatly enhance the exchange of gases such as CO_2 and dimethyl sulfide across the air-sea interface, whereas surfactants, which are scavenged by the rising microbubbles, inhibit gas exchange. The exact magnitude of these effects is not well understood and remains an active area of research [*Wanninkhof et al*., 2009]. The surfactant which has been scavenged by the bubbles and brought to the surface would likely outlive the bubbles. Sea salt aerosol and biological particles are emitted from the sea surface when bubbles burst and produce film or jet droplets, although the small microbubbles in our simulation will only produce jet droplets [*de Leeuw et al*., 2011]. These aerosols can form cloud condensation nuclei which could produce a cooling effect as exploited in marine cloud brightening geoengineering schemes. Neither gas exchange nor bubble-bursting effects were taken into account in our simulations: we cannot say whether the net effect would cause cooling or warming of the climate. However, the use of additional surfactant to increase microbubble lifetime may not be wise if it inhibits ocean uptake of CO_2 and could render this geoengineering scheme unviable. This needs further study.

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