Dust in the Earth system: The biogeochemical linking of land, air, and sea

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Understanding the response of the Earth's climate system to anthropogenic perturbation is a pressing priority for society. To be successful in this enterprise we need to analyze climate change within an all-encompassing "Earth system" framework; the suite of interacting physical, chemical, biological, and human processes that, in transporting and transforming materials and energy jointly determine the conditions for life on the whole planet. To illustrate the integrative thinking that is required we review the diverse roles played by atmospheric transport of mineral 'dust', particularly in its capacity as a key pathway for the delivery of nutrients essential to plant growth, not only on land, but more importantly, in the ocean. Here, the global importance of dust arises because of the control it exerts on marine plant productivity and thus the uptake of CO_2 from the atmosphere. The complex way in which dust biogeochemically links land, air, and sea presents us with new challenges in understanding climate change and forces us to ask questions that transcend the traditional scientific disciplines.

1. Introduction

Winds can pick up soil particles that are smaller than a few tens of micrometers in diameter and carry them great distances through the

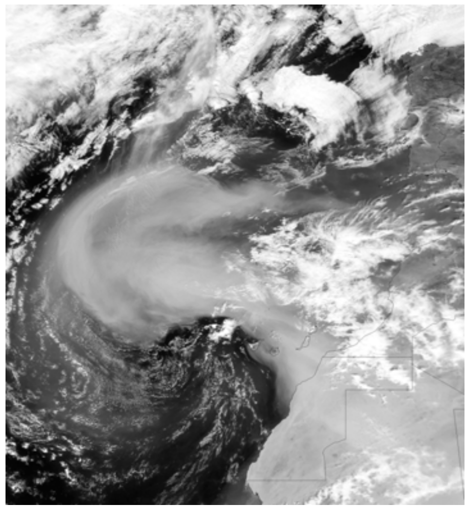

Fig. 1. True color satellite (SeaWiFS) image taken on February 26th 2000 of a massive sandstorm blowing off northwest Africa and reaching over 1000 miles into the Atlantic. (The SeaWiFS image was provided by NASA DAAC/GSFC and is copyright of Orbital Imaging Corps and the NASA SeaWiFS project.)

atmosphere. Although these individual particles are often invisible to the naked eye, billions of tons of material are transported every year in this way. Some of these transport events are even visible from space, as shown in the accompanying satellite image (Figure 1). This ‘dust’ can comprise viruses, pollen grains, and industrial emissions such as soot. Over the ocean, sea salt particles produced by breaking waves and subsequent evaporation of water droplets are a major constituent of atmospheric aerosols. In this review, however, we consider dust to be soil mineral fragments.

The entrainment of dust from the land surface into air depends on several factors, including the surface vegetation cover, wind speed, and the properties (texture and moisture content) of soil. Dust is primarily emitted from regions lacking dense vegetation, i.e., regions where less than approximately 15% of the ground is covered. It is not surprising then to discover that dust sources are predominantly restricted to arid and semi-arid regions with desert, grassland, or shrubland vegetation

(Prospero et al., 2002). In these sparsely vegetated areas, the wind speed across the surface must be great enough to lift particles into the air. This critical wind speed is called the "threshold velocity" and depends on the surface properties of the soil. Silt-sized particles are easiest to lift and require the lowest surface wind speeds to become airborne, while larger particles are heavier and have higher threshold wind velocities. The smallest, clay-sized particles have a larger surface area-to-volume ratio and tend to adhere to each other. Thus higher wind speeds are required to overcome the cohesive forces holding these particles together. The ability to lift dust into the air also depends on the moisture content of the exposed soils, as moisture tends to increase cohesion between soil particles.

How much dust enters the atmosphere? The most recent studies estimate that between 1000 and 2150 Tg (10^{12} grams) of dust is emitted each year (Zender et al., 2004). This wide range of estimates results from two factors. First, it is very difficult to obtain observational datasets that are extensive and detailed enough to quantify dust emissions on a global scale. Second, global models used to estimate the mobilization and transport of dust parameterize the controlling factors differently. For similar reasons, our knowledge of the atmospheric burden, or the amount of dust that remains in the atmosphere, is even less concise. Estimates of the atmospheric burden of dust vary by a factor of four, ranging from 8 to 36 Tg (Zender et al., 2004).

While heavier particles rapidly settle out of the air and are deposited close to their source, finer particles remain suspended in air and can be transported great distances by the prevailing winds. Eventual deposition to the Earth's surface occurs either through 'dry' depositional processes such as gravitational sedimentation or turbulent transfer, or through 'wet' depositional processes such as entrainment into falling raindrops ('precipitation scavenging'). All of these factors, in conjunction with atmospheric circulation, combine to create the distribution of dust deposition shown in Figure 2. Particularly high rates are observed immediately downwind of the Sahara and Sahel deserts of North Africa and extend across the Atlantic to the Caribbean and northeastern South America. High deposition rates are also found over the northwestern Pacific and northeast Indian Oceans, associated with the deserts of

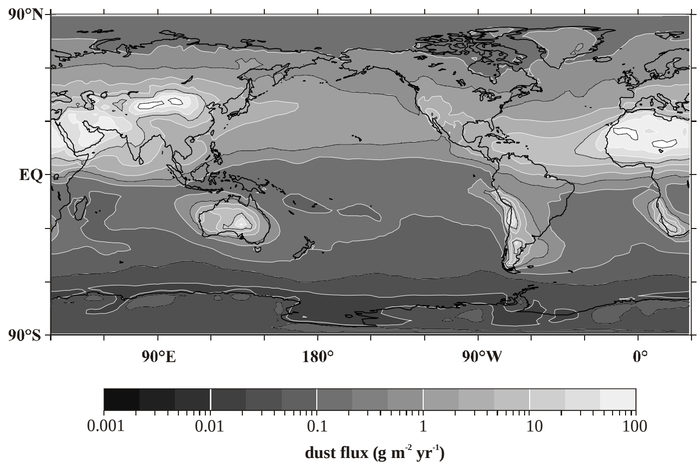

Fig. 2. Model simulated distribution of the annual mean (1981-1997) rate of dust deposition to the Earth's surface (Ginoux et al., 2002).

central Asia. Less extensive dust sources in Australia, southern Africa and Patagonia have more localized influences. In contrast, marine locations remote from any major dust sources, such as the Southern Ocean, are characterized by dust deposition rates that are 100-1000 times lower than rates found immediately downwind of North Africa.

Dust also affects the optical properties of the atmosphere by modifying incoming (ultraviolet and visible) and outgoing (infrared) radiation. According to climate models, dust aerosol can cause localized seasonal heating (over light-colored surfaces) or cooling (over dark-colored surfaces) by as much as ±2°C (Miller and Tegen, 1998). Another local heating effect can occur when dust is deposited on snow. Dust darkens the surface and decreases the fraction of sunlight that is reflected. This effect has been suggested as important in helping to melt the great ice sheets of the Northern Hemisphere at the end of the last ice age (Peltier and Marshall, 1995). Finally, dust suspended in the atmosphere may affect climate by influencing cloud nucleation. It is when dust modifies the flow of carbon and nutrients within the Earth system ('global biogeochemical cycling'), however, that it arguably plays its most fascinating and intricate role.

2. Dust deposition in the terrestrial realm

Wind-blown dust that settles on the land surface can accumulate to great thickness. For instance, over the past few million years, dust carried from Asian deserts to the Loess Plateau region of China has accumulated into soil sequences of up to 200 m thick. Dust influences soil structure even in places where deposition rates are considerably lower. For instance, aeolian quartz can become a major soil constituent when the underlying substrate is highly susceptible to weathering. On the basaltic bedrock of the Hawaiian Islands, much of the soil has literally come all the way from China and central Asian deserts (Kurtz et al., 2001)! Dust exerts an important biogeochemical control upon ecosystem structure and plant productivity in these environments because its mineralogy and grain size strongly influence the water- and nutrient-holding properties of the soil.

Dust also plays a more direct biogeochemical role in terrestrial ecosystems. In parts of Amazonia, the soils are already highly weathered and nutrient-depleted, and the nutrient supply from rivers is likely not sufficient to maintain the nutrient balance of the rainforest on timescales of hundreds to thousands of years. In this region, aeolian deposition of nutrients such as phosphorous may be critical (Swap et al., 1992). Dust transported across the Atlantic from the deserts of the Sahara and Sahel (such as occurs during periodic dust storms – see Figure 1) might then influence the maximum size of the ecosystem that can be supported. The highly weathered soils and phosphorous-limited ecosystems of some of the older Hawaiian Islands suggest an analogous situation, with losses due to leaching and immobilization of this vital nutrient exceeding local supply (Chadwick et al., 1999). Again, aeolian phosphorous transported across the ocean (this time the Pacific) is required to balance the nutrient budget of the ecosystem. Dust can therefore link the land surface of two physically remote landmasses. A change in one ecosystem, particularly a change to arid or semi-arid vegetation therefore has the potential to affect the productivity of the second ecosystem.

3. Dust deposition in the marine realm

The major nutrients required by the primary producers of the open ocean (microscopic marine plants – ‘phytoplankton’) are phosphate (PO_4^{3-}), nitrate (NO_3^-). Many species also require calcium or dissolved silica to construct their shells. These primary producers live and grow in the surface layers of the ocean where they receive sufficient sunlight for photosynthesis, and are kept for the most part from mixing into the deeper layers of the ocean by strong temperature and density gradients. As phytoplankton cells grow and divide, nutrients are removed from solution and transformed into cellular constituents. Most of this material is degraded by the action of bacteria and zooplankton near the surface and returned into solution within the mixed surface layer. However, a small (but important) fraction, in the form of dead cells, zooplankton fecal pellets, and other particulate organic debris sinks below the surface layer and is broken down much deeper down in the ocean. Although the nutrients released even at depths of several km will eventually be returned to the surface by upwelling and mixing, a vertical gradient is created with lower nutrient concentrations at the surface than in the deep ocean. This removal by the biota of dissolved constituents from the surface waters and export of nutrients (in particulate form) to depth is known as the ‘biological pump’.

3.1. *Iron limitation in the ocean*

A long-standing puzzle in oceanography has been why phytoplankton do not always fully utilize the nitrate that is supplied to them by the circulation of the ocean and thus why the biological pump does not always work at its maximum possible rate. In certain areas of the world ocean and the Southern Ocean in particular, high concentrations of NO_3^- remain in surface waters (Figure 3). A similar situation prevails for PO_4^{3-} (not shown). Despite the availability of NO_3^-, standing stocks of phytoplankton are relatively low, leading to the designation of such regions as ‘High-Nutrient Low-Chlorophyll’ (HNLC). Although physical conditions (such as low light levels) and the intensity of grazing by

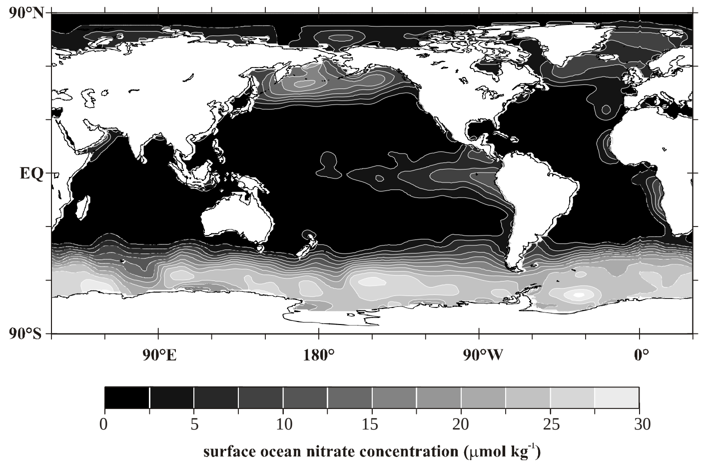

Figure 3. Global distribution of near-surface (30 m depth) ocean nitrate (NO_3^-) concentrations (Conkright et al., 1994).

microscopic marine animals ('zooplankton') can help account for the HNLC condition they are not sufficient explanations on their own.

In the late 1980s came the idea that insufficient availability of iron might also restrict phytoplankton growth (Martin and Fitzwater, 1998). Iron is essential for enzymatic activities associated with photosynthesis. Laboratory experiments demonstrated that the addition of Fe to HNLC water samples almost invariably stimulated phytoplankton growth and increased NO_3^- uptake. However, because the *in vitro* environment differs in a number of crucial respects from that of the ocean, the results of these small-scale experiments could not unambiguously tell us what was happening out in the open ocean.

A methodology for carrying out Fe fertilization of the ocean was devised (Watson et al., 1991), involving the dispersal of dissolved Fe from a ship whilst simultaneously marking the resulting 'patch' of enhanced Fe with an easily measurable label such as the inert tracer sulphur hexafluoride (SF_6). Following Fe release, the patch is crisscrossed, and observations made both within and outside the patch (as defined by the presence or absence of SF_6 in the water, respectively).

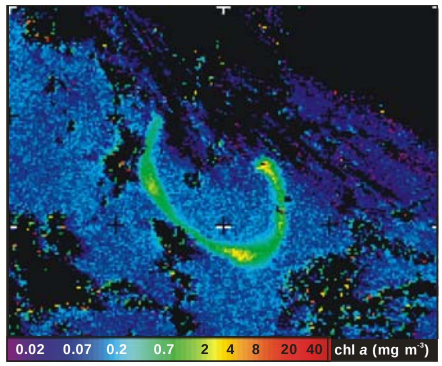

Figure 4. Ocean color satellite (SeaWiFS) image of surface ocean chlorophyll *a* concentrations some 6 weeks after the deliberate release of iron in the Southern Ocean. The fertilized ocean patch appears as a ribbon of high chlorophyll *a* concentrations ~100 km across. Cloud cover is indicated by black regions. (SeaWiFS data provided by the NASA DAAC/GSFC and copyright of Orbital Imaging Corps and the NASA SeaWiFS project, and processed at CCMS-PML.)

The water outside acts as a 'control' on any changes measured in the Fe-enriched patch.

One such experiment was carried out in February of 1999 in the Southern Ocean – the 'Southern Ocean Iron RElease Experiment' (SOIREE) (Boyd et al., 2000). As hypothesized, the phytoplankton responded to the addition of Fe with a strong increase in the concentration of chlorophyll *a* within the fertilized patch but not outside it. (Chlorophyll *a* is a phytoplankton photosynthetic pigment whose concentration can be taken as a rough indicator of cell density.) In SOIREE, the impact of iron fertilization was so striking that the results of the experiment were visible from space! Six weeks after the initial Fe release, gaps in the cloud cover allowed the remote sensing of surface ocean optical properties with the satellite image (Figure 4) showing a 'bloom' of enhanced chlorophyll concentrations compared to the surrounding waters.

3.2. *Iron supply to the surface ocean*

Why should there be a deficit (relative to other nutrients) in the supply of iron to the biota, in some locations in the ocean but not others? Transport by rivers is the dominant route by which Fe is supplied to the ocean as a whole. But before it can reach the open ocean, rapid biological uptake and sedimentation in highly productive estuaries and coastal zones tends to remove much of the newly supplied Fe from the water. Rivers are therefore not thought to be an important source of Fe to the open ocean. As with NO_3^-, supply of Fe to the surface ocean occurs through upwelling and mixing of ocean waters from below. However, dissolved Fe has a short lifetime in the oxygenated seawater environment. Fe^{II}, the most soluble state, is rapidly oxidized to Fe^{III} which is highly insoluble and tends to be removed from solution by attaching to particulate matter settling through the water column (Jickells et al., 2005).

The result is that the concentration of Fe is low in upwelling water relative to that of the highly soluble NO_3^-. Consequently phytoplankton in surface waters cannot fully utilize the abundant nitrate unless more Fe is brought into the system. Dust becomes important in these iron-depleted surface waters, because mineral aerosols contain about 4% iron by weight (oxygen, silicon, and aluminum accounting for almost all the remainder). Dissolution of this iron in surface waters has the potential to supply the shortfall in upwelled Fe supply and enable phytoplankton to completely utilize all available NO_3^-.

The distribution of dust deposition to the ocean (Figure 2) shows that fluxes to the Southern Ocean are amongst the lowest anywhere on Earth. The aeolian supply is too small to compensate for the depleted Fe relative to NO_3^-. Consequently phytoplankton cannot fully utilise the available NO_3^-. Similar reasoning also explains the high NO_3^- pool of the Eastern Equatorial Pacific (Figure 3). Dust supply to the North Pacific appears moderately high, but fertilization experiments in the Northwest Pacific (Tsuda et al., 2003) suggest that this region is still iron-limited. Observations of natural dust-fertilization events in the Northeast Pacific have shown that Asian dust is a significant source of iron today and can increase carbon biomass in the surface waters (Bishop et al., 2002).

3.3. *Iron supply and the global carbon cycle*

The concentration of dissolved inorganic carbon (DIC) in the surface ocean exerts a fundamental control on air-sea CO_2 exchange along with other factors such as ambient temperature, *p*H, and wind speed. Processes that affect DIC will therefore influence the concentration of CO_2 in the atmosphere, and with it, climate (via the 'greenhouse effect'). One process that affects DIC concentrations is the biological removal of carbon from surface waters. Phytoplankton utilise carbon as well as nutrients at the ocean surface and incorporate it into cellular organic constituents. When biological activity reduces surface water DIC, the equilibrium concentration of gaseous CO_2 is depressed, driving a net transfer of CO_2 from the atmosphere into solution in the ocean. The concentration of CO_2 in the atmosphere will then exhibit an inverse relationship to the strength of the biological pump. Indeed, in the absence of any biological activity in the ocean, atmospheric CO_2 would be about 50% higher than it is today. Thus, changes in dust and iron supply to the ocean that modify the strength of the biological pump then have the potential to affect atmospheric CO_2 and climate.

4. Anthropogenic modification of dust supply

The present-day supply of Fe to high-nitrate low-chlorophyll (HNLC) regions is not large enough for the ocean's biological pump to work at its maximum efficiency and fully utilize all supplied NO_3^-. In addition, other regions such as the central tropical Pacific and north Atlantic may be close to limitation or quasi-limited by Fe. Any reduction in dust supply will intensify limitation where it already exists and potentially induce limitation of productivity elsewhere. Either way, if aeolian Fe fluxes were lower, there should be a reduction in the rate of CO_2 uptake by the ocean, which has implications for atmospheric CO_2 concentrations and the rate and degree of future climate change. Under what circumstances might a reduction in dust supply to the ocean occur? Answering this question involves clarifying the two different types of anthropogenic contributions to atmospheric dust (Zender et al., 2004). Humans can influence the production of dust directly by altering the land surface.

Alternatively, humans can indirectly affect the atmospheric dust burden through the cumulative impact of anthropogenic climate changes on the dust cycle.

The deliberate large-scale manipulation of terrestrial ecosystems has been proposed for the ‘locking up’ (sequestration) of carbon on land. These include, changes in soil management practices such as reducing tillage, enhancing the areal and seasonal extent of ground cover, and the ‘setting-aside’ of surplus agricultural land, in addition to the restoration of previously degraded lands and forestation (Royal Society, 2001). However, reduced disturbance, stabilization of soils, and greater vegetation cover are also likely to reduce dust emissions. Since dust exerts an important control on the biological pump in the ocean, the effectiveness of carbon sequestration on land may be diminished by a reduction in carbon uptake by the ocean.

Early models of dust transport and deposition suggested that a substantial (30-50%) component of the present-day global dust supply originated in disturbed soils (Tegen and Fung, 1995). If these soils were stabilized in the future for sequestering carbon, a substantial decrease in global dust emissions would occur. Computer models suggest that a 30% reduction in dust flux to the global ocean would lower ocean productivity to such an extent that the weaker ocean carbon sink could potentially offset the benefit of sequestering carbon on land (Ridgwell et al., 2002), leaving atmospheric CO_2 unchanged. However, subsequent satellite-based analyses suggest that the anthropogenic component is much smaller (Prospero et al., 2002). Furthermore, more recent attempts to match dust model simulations to the surface observations have suggested agricultural practices contribute less than 10% to the total global atmospheric dust burden (Tegen et al., 2004b), although limited surface observations make this number difficult to ascertain exactly (Mahowald et al., 2004; Tegen et al., 2004a). These more recent results suggest that a 30% reduction in dust production due to land-use changes are not likely.

Socio-economic and political factors are likely to ultimately dictate any future large-scale alteration of the land surface, with changes in dust supply probably occurring on a regional scale rather than globally. For instance, a massive reforestation program is already under way in China with the specific intention of combating soil erosion and associated dust storms. Although several recent studies have demonstrated that climate factors play a strong role in determining the frequency of dust storms over China (Mukai et al., 2004; Zhao et al., 2004), changes in reforestation could have (as yet unquantified) implications for marine ecosystems in the iron-sensitive equatorial and North Pacific.

The second means by which human activity could affect dust emissions is through anthropogenic climate change. A change in climate could drive an increase in vegetation cover in arid areas, reducing the supply of dust to the atmosphere (Harrison et al., 2001). The efficiency with which dust is transported through the atmosphere may also change, with any increase in global precipitation removing more dust before it reaches the open ocean. However, current model simulations have not reached a consensus regarding the impact of future climate on dust emissions. While some simulations suggest that dust emissions will decrease by as much as 60% by 2090 (Mahowald and Luo, 2003), other simulations suggest that dust emissions might even increase by as much as 10%. Thus, the response and even the direction of change of future dust emissions is highly dependent on the climate model used (Tegen et al., 2004b).

Current computer carbon cycle models only give a relatively crude indication of the possible impacts. Such experiments do, however, serve to highlight the important link within the Earth system that is mediated by dust; a connection between carbon cycling and climate and human activities that was previously completely overlooked. The rather narrow and restricted land-atmosphere approach to carbon budgeting in the Kyoto Protocol that neglects important Earth system feedbacks involving the ocean is then too simplified.

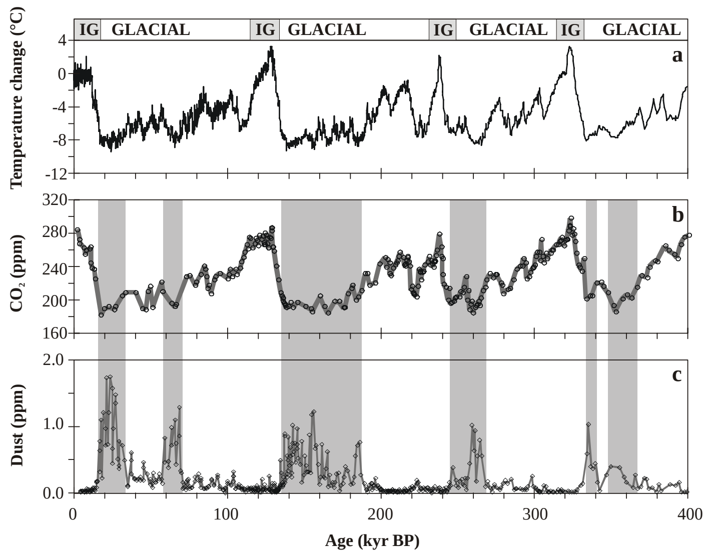

Fig.5. Key indicators of climatic state contained within the Vostok ice core (Petit et al., 1999). a, Isotopically-derived temperature change (relative to the present) at the surface. Cold glacial and warmer interglacial ('IG') intervals are indicated. b, CO_2 concentration in air bubbles contained within the ice. c, Dust concentration in the ice. The correspondence between CO_2 minima and prominent dust peaks are highlighted.

5. The demise of the last ice age: a role for dust?

The Earth has experienced a series of intense ice ages over the course of the last million years or so. Each ice age ended rather suddenly, with a rapid warming transition ('termination') from cold glacial conditions into a (relatively brief) mild interglacial period (Figure 5a). Many different theories have been advanced for how these cycles might be driven. These have typically focused on the physical climate system, particularly interactions between ice sheets and underlying bedrock with external forcing provided by orbitally-driven variations in the seasonal intensity of sunlight received at the Earth's surface. However, such explanations fail to correctly predict the amplitude and timing of the observed cyclically in global ice volume, suggesting that additional factors might also be critical (Ridgwell et al., 1999).

Records of past atmospheric composition, in the form of microscopic bubbles of ancient air trapped within the crystalline structure of ice sparked a revolution in understanding of what drives these ice age cycles. Cores of ice recovered from Antarctica and analyzed for air bubble gas composition revealed that atmospheric CO_2 varies cyclically between about ~280 ppm during interglacials and ~190 ppm during the most intense glacial periods (Figure 5b).

What causes the observed variability in CO_2? A possible clue comes from the changes in dust deposition, also recorded in the Vostok ice (Figure 5c). The concentration of dust contained within the ice exhibits a series of rather striking peaks against a background of relatively low values; a much greater dynamic range than can be accounted for by dilution effects arising from changes in snow accumulation rate alone. The occurrence of these peaks correlates with periods of particularly low atmospheric CO_2 values. This is certainly consistent with increased dustiness during glacial times providing more iron to the surface and driving a more vigorous biological pump in the ocean (Martin, 1990; Watson et al., 2000). However, investigations of the global carbon cycle using both numerical models (Archer et al., 2000; Bopp et al., 2003) and observations (Bopp et al., 2003; Kohfeld et al., 2005) suggest that an increase in the strength of the biological pump can only be part of the explanation for low glacial atmospheric CO_2 concentrations. Other mechanisms must be at work.

If dust is responsible for some of the observed glacial-interglacial variability in atmospheric CO_2, then we need a much better understanding of the factors that bring about changes in dust fluxes. Elevated glacial dust fluxes are not restricted to Antarctica. In fact, similar features are found in dust records from ice, marine, and terrestrial environments around the world. A colder, drier glacial climate, with a less vigorous hydrological cycle would result in decreased precipitation scavenging, more efficient transport of dust, and thus higher deposition rates. However, models of dust generation, transport, and deposition suggest that a reduction in the hydrological cycle alone is not sufficient to explain the increases in glacial dustiness. Greater source strengths of dust must also be invoked. The expansion of arid areas under cold, dry glacial climatic conditions, or even the exposure of continental shelves as the ice sheets grow and sea-level drops could result in new sources of dust. Furthermore, higher wind speeds during the glacial period could result in enhanced entrainment from existing source areas (e.g., Mahowald et al., 1999; Werner et al., 2003). Thus, changes in sea-level, aridity, and vegetation type and cover, as well as atmospheric circulation, and precipitation strength and patterns all combine to affect dust deposition, and with it, atmospheric CO_2 and climate (Ridgwell and Watson, 2002).

6. Conclusion and Perspectives

We are just embarking on a radical new integrated view of how the Earth system functions on a range of timescales (Schellnhuber, 1999). This holistic view will be critical if we are to understand the complex and sometimes unexpected behavior of the climate system that arises out of a high level of interaction and interconnectedness. Indeed, even individual sub-systems such as that involving dust (Figure 6) can exhibit highly complex and non-linear behavior, because dust is much more than simply as a passive ‘communicator’ of events between components of the Earth system (Jickells et al., 2005). For instance, if changes in dust flux affect atmospheric CO_2 and climate, and dust fluxes are in turn responsive to global climate through changes in the land surface and the strength of the hydrological cycle, this raises the possibility of a ‘feedback’ (Ridgwell, 2003; Ridgwell and Watson, 2002) (highlighted in Figure 6). In such a system, any global cooling that occurs, such as the descent into a glacial state, could produce an increase in dust availability and transport efficiency. This could, in turn, drive a decrease in CO_2 through Southern Ocean iron fertilization, causing a further cooling and thus further enhanced dust supply, etc. This ‘positive’ feedback will amplify the magnitude of the initial perturbation (climate cooling). This same dust feedback may also amplify any future climate change that is initially driven by CO_2 emissions from fossil fuel burning.

To fully understand the complicated role of feedbacks and overall behavior of the operation of the climate system, we need fresh investigative tools – numerical models of the Earth system (e.g., ‘genie’ http://www.genie.ac.uk/). By coupling together representations of ocean and atmospheric circulation, cryosphere, and descriptions of the primary biogeochemical cycles that permeate the land, atmosphere, ocean, and sediments, the operation of the climate system on a range of time scales can be comprehensively explored. If these models are further extended by integration with socio-economic models, the interaction between the climate system and anthropogenic activities can be addressed. Climate-socio-economic ‘Integrated Assessment Models’ are currently being actively developed by institutions such as the UK Tyndall Centre (http://www.tyndall.ac.uk/), and will greatly aid us in deciding how we might mitigate and adapt to future climate change.

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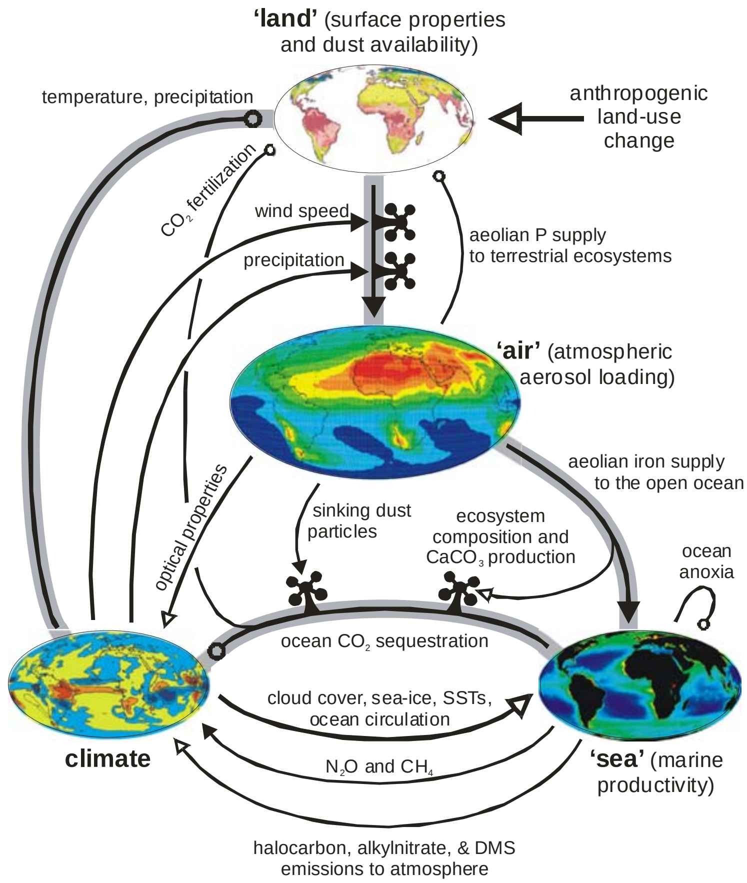

Figure 6. Schematic view of the linking of land, air, and sea (and climate) by dust. (Adapted from Jickells et al., 2005). Highlighted are four critical components of the Earth system, (clockwise from top); state of the land surface and dust material availability ('land'), atmospheric aerosol loading and dust deposition ('air'), marine plankton productivity ('sea), and climatic state (e.g., mean global surface temperature). The biogeochemical connections between them can have a positive correlation (e.g., increased atmospheric aerosol loading and dust deposition results in increased in marine productivity) indicated by a filled arrowhead, or a negative correlation (e.g., increased marine productivity leads to lower atmospheric CO_2 and a colder climate), indicated with an open circle. An open arrowhead indicates where the sign of the correlation is uncertain. The 'taps' represent where a mechanism affects the strength of a connection between two components rather than affecting a component directly. A change in global precipitation strength altering the efficiency with which entrained dust is transported out to the open ocean is a good example of this. Shown back-highlighted (grey lines) is the positive feedback; atmospheric aerosol loading → marine productivity → climatic state → dust availability → atmospheric aerosol (Ridgwell, 2003; Ridgwell and Watson, 2002).

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