Chapter 6

CONCLUSIONS

In this work I propose two modifications to make the sea-salt generation function currently used in climate models more relevant for studies of aerosol effects on climate. Assimilating whitecap coverage estimates obtained with a new method, the sea-salt generation function accounts for the influence of various environmental factors on the production of sea-salt aerosols. In addition, the sea-salt generation function needs extension of its applicability toward smaller sea-salt aerosol sizes. I believe that the generation function thus modified predicts more realistic loading of sea-salt aerosols into the atmosphere. As a consequence, the modified generation function provides more realistic evaluations of the direct and indirect contributions of sea-salt aerosols to climate processes, and their contribution to atmospheric chemistry.

To implement the modifications, I have developed a new method for estimating whitecap coverage from satellite-measured brightness temperature of the ocean surface. The retrieved whitecap coverage incorporates the effects of various environmental and meteorological variables. The method provides estimates of the whitecap coverage on a global scale with an accuracy comparable to and often better than that of *in situ* measurements. Satellite-derived estimates of whitecap coverage accompanied with measurements of wind speed, sea surface temperature, and salinity were compiled into an extensive database. Data in the whitecap coverage database facilitate investigation of the spatial and temporal characteristics of global oceanic whitecaps, and allow new parameterizations of whitecap coverage in terms of sea surface temperature and salinity.

The necessity to improve some aspects of the current generation function motivates this work. The inclusion of the effects of sea-salt aerosols improves the predictions of climate models. The generation of sea-salt aerosols is the first of many processes that must be modeled. Oceanic whitecaps are the major source of sea-salt aerosols. Sea-salt aerosols are the dominant natural aerosols in remote marine air and contribute to radiative and chemical processes affecting climate. Modeling the production of sea-salt aerosols usually needs whitecap coverage, W, and its dependence on wind speed, U_{10}. Various measurements of sea-salt production, however, do not constrain well the predictions of the sea-salt generation function using the relation $W(U_{10})$ alone. Other variables, beside wind, affect the formation of whitecaps and production of sea-salt aerosols.

A list of the major results on global whitecap coverage and the production of sea-salt aerosols, as well as suggestions for future work follow.

6.1 Major results

6.1.1 Global whitecap coverage

A new method, built on the concept that the microwave emissivity of a foam-covered ocean differs from that of a foam-free ocean, provides estimates of whitecap coverage on a global scale. Satellite-borne Special Sensor Microwave/Imager (SSM/I) supplies data for brightness temperature, which is a measure for the ocean emissivity and whitecap coverage. Data preparation and atmospheric correction necessary for implementing the method use additional satellite and *in situ* data.

An analytical investigation sets up expected values for ocean emissivity in different regimes (composite, specular, roughened, and foamy water) and reveals those environmental conditions, which yield plausible estimates of whitecap coverage. The assimilation of real data in the computational algorithm proves the feasibility of the method.

An advantage of the new method is the possibility of estimating whitecap coverage over the globe on a daily basis under various meteorological and environmental conditions. Until now whitecap coverage has been measured from photographs of the ocean surface. Data processing of these *in situ* measurements is unavoidably subjective, which adds to the uncertainty of whitecap measurements. Some remote sensing algorithms retrieve whitecap coverage as a by-product. The method I offer is a first attempt to develop an objective and stand-alone algorithm for remote measuring of whitecap coverage.

A thorough error analysis of the algorithm for obtaining whitecap coverage establishes the most common conditions that preclude valid retrievals: whitecap coverage cannot be retrieved reliably under low winds and moist atmosphere. The new method estimates whitecap coverage with a maximum error of one standard deviation, that is, a relative error less than 100%. About 50% of the whitecap coverage estimates have relative error below 30% down to about 8%. This is an improvement in the accuracy of estimating whitecap coverage compared to that of *in situ* measurements from photographs.

The new method is validated by comparison of satellite-derived estimates of whitecap coverage with values of whitecap coverage obtained from previous *in situ* measurements and calculations from wind speed. The validation shows that the new method estimates the global whitecap coverage successfully.

6.1.2 Whitecap coverage database

With the new method I estimated whitecap coverage on a global scale for all days of 1998. Daily and monthly estimates of whitecap coverage, W, accompanied with their corresponding standard deviations and concomitant measurements of wind speed, U_{10}, sea surface temperature, T_s, and salinity, S, built a comprehensive database. This database offers a wealth of information about the global whitecap coverage, whose investigation both confirms some previously reported contentions and reveals new features.

Global whitecap coverage is about 3%. This values is consistent with the Blanchard (1963) estimate of global whitecap coverage, but is 2.5 to 3 times higher than the global whitecap coverage estimated from the existing wind-speed relation, $W(U_{10})$. I explain the higher values of whitecap coverage with: i) the ability of the new method to measure both active (A-stage) and decaying (B-stage) whitecaps; ii) better sampling of vast areas of the world ocean, especially areas in the Southern Ocean; iii) estimation of whitecap coverage from daily values of brightness temperature instead of monthly values of wind speed.

Estimates of whitecap coverage with the new method contain the effects of various meteorological and environmental factors, namely wind speed, U_{10}, atmospheric stability, ΔT, sea surface temperature, T_s, water salinity, S, wind fetch, f, wind duration, d, and surfactant concentration, C. The composite effect of all these factors leads to two noticeable characteristics of satellite-measured whitecap coverage, which the wind-speed relation, $W(U_{10})$, does not predict.

First, whitecap coverage has higher variability than expected at a given wind speed. This fact corroborates nicely the observed high variability of sea-salt fluxes, which the $W(U_{10})$ relation alone cannot explain.

Second, the global whitecap coverage has a more uniform spatial distribution than that predicted by $W(U_{10})$. Specifically, high whitecapping in high latitudes is not as dominant a feature in the spatial distribution of the satellite-derived whitecap coverage as the $W(U_{10})$ relation implies. Whitecap coverage in high latitudes could be comparable to or less than that in mid and low latitudes. Whitecap coverage is up to 4-6% along the trade wind belts (15° to 30° N and S) and in the zones of the prevailing westerlies (30° to 60° N and S). The lowest values of whitecap coverage, up to 1%, are north and south of the equator and on the western edges of the continents.

The interplay between the effects of wind speed and water temperature partially explains the high variability and more uniform spatial distribution of the satellite-measured whitecap coverage. The effect of sea surface temperature is mostly in altering the expected effect of the wind. Low water temperatures suppress the effect of high winds, while high water temperatures enhance the effect of low to moderate winds. The consequence is that low to moderate winds (5-12 m s^{-1}) blowing over warm waters may create whitecap coverage comparable to that resulting from higher winds over cold waters.

Whitecap coverage shows little seasonal change, from 2.5% to 3.5%, because of a more uniform zonal distribution. The annual seasonal cycle reaches its peak during the austral winter due to high whitecap coverage in the Southern Ocean.

The albedo of a foam-covered ocean surface increases compared to the albedo of a foam-free ocean. As a result of whitecaps, the amount of reflected solar radiation increases on average by 0.11 W m^{-2} compared to an ocean with no whitecaps. In this way oceanic whitecaps provide natural cooling of the climate system comparable in magnitude to the cooling by such anthropogenic agents as stratospheric ozone, biomass burning, and land use.

The assimilation of satellite-derived estimates of whitecap coverage in the existing parameterization schemes yields values for gas transfer velocity of CO_2 in the range 5-150 cm h^{-1} with a global average of 56.8 cm h^{-1}.

The effects of sea surface temperature, T_s, and water salinity, S, are parameterized, and the relation $W(U_{10})$ is extended to $W(U_{10}, T_s, S)$. Regression analysis is a suitable tool for this parameterization, but the method of least squares used to obtain the regression coefficients proves to have weaknesses, such as a frequent failure of the tests of normality and constant variance due to the high variability of whitecap coverage. Procedures to circumvent these weaknesses are proposed, and the parameterization of the effect of sea surface temperature is successfully carried out. The parameterization of the salinity effect fails in this first attempt mostly due to the use of a narrow range of salinity values. Parameterization with an exponential-law model in the form $W(U_{10}, T_s) = a(T_s)\exp[b(T_s)U_{10}]$ proves to be a better predictor of whitecap coverage than the $W(U_{10})$ relation. However, the new $W(U_{10}, T_s)$ relation still cannot predict the full range of variability of the whitecap coverage under moderate winds. The parameterization of the effects of sea surface temperature and salinity is a first attempt, and though not completely successful, the initial results are encouraging.

6.1.3 Generation of sea-salt aerosols

In this work I modify the current generation function of sea-salt aerosols to include the effects of various environmental factors on the production of sea-salt aerosols, and to extend it toward smaller sizes relevant for climate studies. I implement the first modification by assimilating global fields of whitecap coverage, obtained with the new method, into the sea-salt generation function. To extend the applicability of the generation function for small sea-salt aerosol sizes, I use various size dependences. The size dependence of the current generation function proposed by Andreas (2002) is the best available one over the range of 1.6-20 μm. Though beyond its range of applicability, the size dependence of Monahan et al. (1986) works well over the range of 0.4-1.6 μm.

Using the modified generation function I computed sea-salt aerosol loadings into the atmosphere for all months of 1998. The calculations give the sea-salt aerosol production in different terms such as number, volume, surface, and mass fluxes, as well as number and mass concentrations. The total mass of sea-salt aerosols produced by the world oceans is around 2×10^{16} g yr^{-1}.

The spatial and temporal characteristics of sea-salt aerosols mimic those of whitecap coverage. Sea-salt aerosol flux in mid and low latitudes is higher than that predicted by the generation function involving wind effect only. The main reason is the influence of sea surface temperature on the formation of whitecaps.

I examined the performance of the modified generation function by comparing its results with the predictions of the current generation function and *in situ* observations. The modified generation function predicts sea-salt aerosol production of the same order of magnitude as that predicted by the current generation function. The main and important difference is in the spatial distribution of the sea-salt fluxes.

Evaluation of the effects of sea-salt aerosol loading obtained with the modified generation function to various climate processes confirms the significance of sea-salt aerosols for the climate system. The contribution of sea-salt aerosols to the reflection of incoming sunlight could be as high as 15 W m^{-2}. The optical thickness of a layer of sea-salt aerosols in clean atmosphere is about 0.4. This value can serve as a baseline for assessing the optical thickness and radiative forcing of an aerosol layer containing anthropogenic species.

Sea-salt aerosol loadings estimated with the modified generation function may create from 1 up to 150 cm^{-3} cloud condensation nuclei depending on the wind speed. Over the oceans, up to 83% of the shortwave radiation could be reflected by marine clouds whose droplets grow on cloud condensation nuclei formed on sea-salt aerosols.

Sea-salt aerosols could deliver 1.1×10^{16} g yr^{-1} of particulate Cl and 4×10^{13} g yr^{-1} of particulate Br to the atmosphere. The world ocean can emit up to 8.8×10^{15} g yr^{-1} Cl in form of HCl due to dechlorination of sea-salt aerosols. The estimated mass flux of sea-salt aerosols is a source of non-sea-salt sulfates in the atmosphere in the order of 10^{16} g yr^{-1}. Gravitational settling of sea-salt aerosols removes from the atmosphere 10^{15} to 10^{16} g of non-sea-salt sulfates annually.

6.2. Future work

The work reported here does not exhaust the subject of sea-salt aerosol generation and the role of these aerosols in the climate system. The results are encouraging and inspire promising future work.

Further work could improve the method of estimating global whitecap coverage from satellite-measured data. The method needs refined modeling of the dielectric constant of seawater, better understanding and modeling of foam emissivity, and better implementation of the atmospheric correction.

The parameterization of whitecap coverage on wind speed, sea surface temperature, and salinity, $W(U_{10}, T_s, S)$, needs refinement. Some of the possibilities for improving the parameterization include the use of: i) additional data for wind fetch and surfactant concentration to better bin the whitecap coverage data; ii) a wider range of salinity values to better account for salinity variations; iii) regression models involving various mathematical laws and their combinations to better describe the trend in whitecap coverage data; iv) regression methods alternative to the least-square method to better manage the high variability of whitecap coverage.

Close scrutiny of the spatial distribution of whitecap coverage implies that wind fetch and surfactant further explain qualitatively the features of this distribution. Quantification of these effects is thus necessary. An important future task is deriving new parameterizations of whitecap coverage in terms of wind fetch, wind duration, and surfactant concentration.

Extension of the modified generation function for sea-salt aerosol sizes below 0.4 μm is urgently needed. My personal communications with climate modelers confirm that need.

A compelling future work is the identification or derivation of updated and refined procedures for evaluating the contribution of sea-salt aerosol to various physical and chemical processes in the atmosphere. This is a challenging task given the incompleteness of the on-going research on and lack of understanding of many climate processes.

A culmination of this work is the inclusion of the modified generation function in actual climate and chemical transport models. Producing acceptable results with actual models would be an ultimate recognition of this work. I would be more than happy to be involved in such endeavor.