2 Remote Sensing of Parameters Relevant to the Particle Flux in the Ocean Using Meteorological Satellites

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2.1 INTRODUCTION

Knowledge of meteorological oceanographic parameters is crucial for the interpretation of particle flux measurements in the oceans. *In situ* measurements, however, are sparse over the sea and simply not available in large areas like the southern oceans away from ship routes. Satellite-borne Earth observation instruments are the only tools capable of acquiring information about environmental parameters in those areas. Although there are no satellites in orbit so far which are dedicated to particle flux studies, operational meteorological and experimental oceanographic satellites can be used to derive a variety of relevant parameters over the global ocean. Furthermore, the satellite measurements have advantages over the common *in situ* observations in that they provide continuous, reliable, and convenient information.

The Earth-observation instruments can be broadly classified in two groups. Radars and lidars measure actively by emitting own radiation into the atmosphere which is attenuated and backscattered to the satellite. The modified signal has to be interpreted with respect to geophysical parameters. Radiometers passively measure the radiation that is emitted from the Earth-atmosphere system in the infrared and microwave spectral domains or radiation emitted from the Sun at ultraviolet, visible and near-infrared wavelengths which has interacted with the Earth’s surface and atmosphere. Depending on the geophysical parameter of interest one or other method has to be utilized. For example, sea surface temperatures are measured passively at infrared wavelengths near 3.7 or 11 µm where the clear atmosphere is transparent and the sea surface has a high emissivity. Otherwise, the surface wind speed over sea is measured by observing the wind-induced surface roughness which alters the surface reflectivity. This is best done at centimeter wavelengths with both, passive and active instruments.

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The measurement of this surface parameter also requires the use of spectral regions where the radiation passes the atmosphere without strong attenuation. These regions are called atmospheric windows.

The interpretation of radiation measurements obtained from satellite observations requires the inversion of integral equations, hence, the development of retrieval methods which are outlined in Figure 2.1. Unless a retrieval technique for use with single radiometers or synergistic combinations of several instruments is available the measurements are rather useless and the extracted information will remain qualitative only.

Operational meteorological satellites currently flying are the polar orbiting satellites of the NOAA (National Oceanographic and Atmospheric Administration) and the DMSP (Defense Meteorological Satellite Program) series as well as geostationary satellites like METEOSAT, GOES, GMS and INSAT. While the latter carry imaging instruments scanning the visible disk of the Earth every 30 minutes the instruments on polar orbiters scan the Earth's surface and the

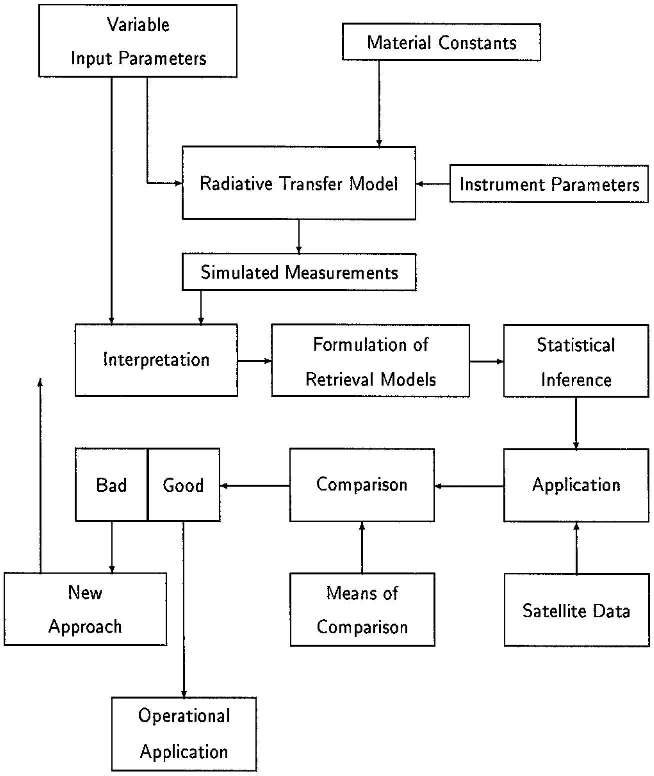

Figure 2.1 Development of a retrieval scheme.

atmosphere on cross-track swaths of 1400 to 3000 km width. Sunsynchronous satellites allow the measurement of most areas two times per day as shown in Figure 2.2 for the Special Sensor Microwave/Imager (SSM/I) which is flown on the DMSP satellites since July 1987. Only 85% of the Earth is seen every day, the remaining diamond shaped areas are monitored within the following three days.

2.2 METEOROLOGICAL PARAMETERS INFLUENCING THE ENVIRONMENT OF PHYTOPLANKTON BLOOMS

The origin of more than 80% of particulate matter reaching the deep ocean is due to phytoplankton blooms. The meteorological parameters influencing the environment of phytoplankton blooms are sea surface temperature (SST), cloud cover, sea ice thickness and distribution, as well as the precipitation.

Sea surface temperature is an indicator of upwelling, entrainment or advection of cooler waters which often are accompanied by higher concentrations of nutrients. Infrared sensors like the AVHRR (Advanced Very High Resolution Radiometer) and the ATSR (Along Track Scanning Radiometer) allow the best retrieval of SST in cloud-free areas utilizing measurements at 3.7, 11, and 12 µm. Observations at two or three wavelengths are combined in order to correct for atmospheric attenuation due to water vapor and aerosols (e.g., McClain et al., 1983; Llewellyn-Jones et al.; 1984, Schlüssel et al., 1987; Minnett, 1990). These methods reach accuracies of about 1 K. More recently, the SST retrieval from AVHRR measurements has been amended by the inclusion of water-vapor information from SSM/I observations in order to allow for higher accuracies close to 0.5 K (Emery et al., 1994). Further improvements of SST measurements from space have been demonstrated with the ATSR (flying on the ERS-1 satellite) which contains actively cooled detectors providing measurements with less noise than the AVHRR (0.02 K instead of 0.12 K at 11 µm). Additionally, a two-angle view at the same surface elements further enhances the correction of atmospheric effects and thus the measurement errors. Current SST retrievals are believed to be better than 0.5 K (Barton et al., 1992). Unfortunately, when using infrared radiometry the surface temperature retrievals are restricted to cloud-free areas only. Depending on the actual cloud cover a global mapping of SST is possible within one to four weeks.

The cloud cover and cloud thickness control the solar illumination of the ocean. Various methods utilizing satellite imagery in the infrared and visible spectral domains have been developed. A summary and intercomparison was done in the frame of the International Satellite Cloud Climatology Project (ISCCP) as described by Rossow et al. (1985). As a result a unified cloud analysis algorithm has been retrieved from this project and applied to global satellite imagery from geostationary and polar orbiting spacecraft. Figure 2.3 shows the zonal

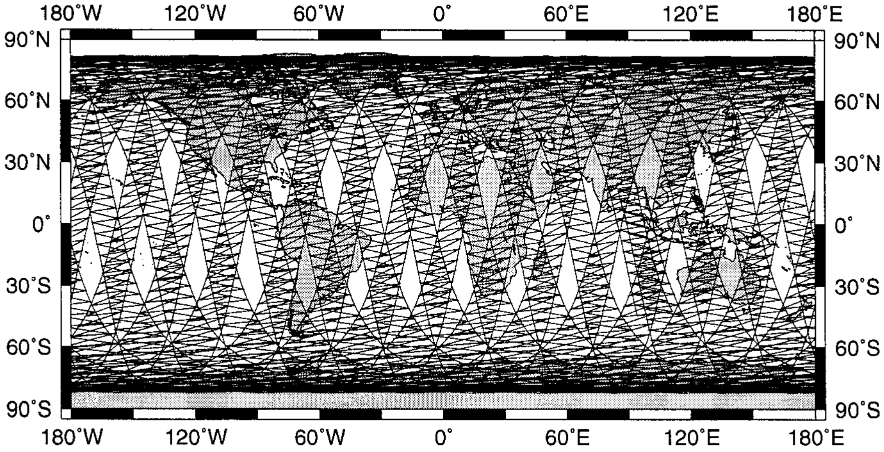

Figure 2.2 Daily coverage of the Earth by the Special Sensor Microwave/Imager.

distribution of average cloud frequencies and optical depths of various cloud types over oceans in 1990 as calculated from the ISCCP data set. The knowledge of these quantities is necessary in order to compute the solar radiation budget at the sea surface which determines the photosynthetically active radiation (PAR) and, hence, the primary productivity in the ocean. Using the ISCCP data together with a retrieval model based on radiative transfer theory Pinker and Laszlo (1992a, b) derive the downwelling solar irradiance at the surface and from that the photosynthetically active radiation. Their results have been mapped globally and presented as time series demonstrating the seasonal and interannual variability. A validation with ground-based pyranometric measurements shows the good performance of their satellite retrievals (Pinker et al., 1993).

Sea ice strongly influences the solar radiation field that is transmitted into the ocean. The photosynthetically active radiation that is available in the upper ocean is determined by the sea ice extent, the type and the thickness of the sea ice. Microwave radiometry is the most valuable tool for the detection and classification of sea ice. It is largely independent from cloud coverage. By partly penetrating into the ice the microwaves allow discrimination between young, first year, and multi-year sea ice (e.g., Comiso, 1986; Cavalieri et al., 1991). The sea ice fields derived from SSM/I measurements agree with aircraft observations within 15%. New methods go even further in classifying new sea ice also using SSM/I observations (Steffen and Schweiger, 1991; Martin and Taurat, 1992). The distribution of different sea ice types is shown in Plate 2.1 for the Arctic and Antarctic areas on February 1, 1988, and August, 1 1988, respectively, as derived from SSM/I vertically polarized measurements at 19.35 and 85.5 Ghz. Measurements from a single satellite have been used to map the sea ice. Only small areas could not be

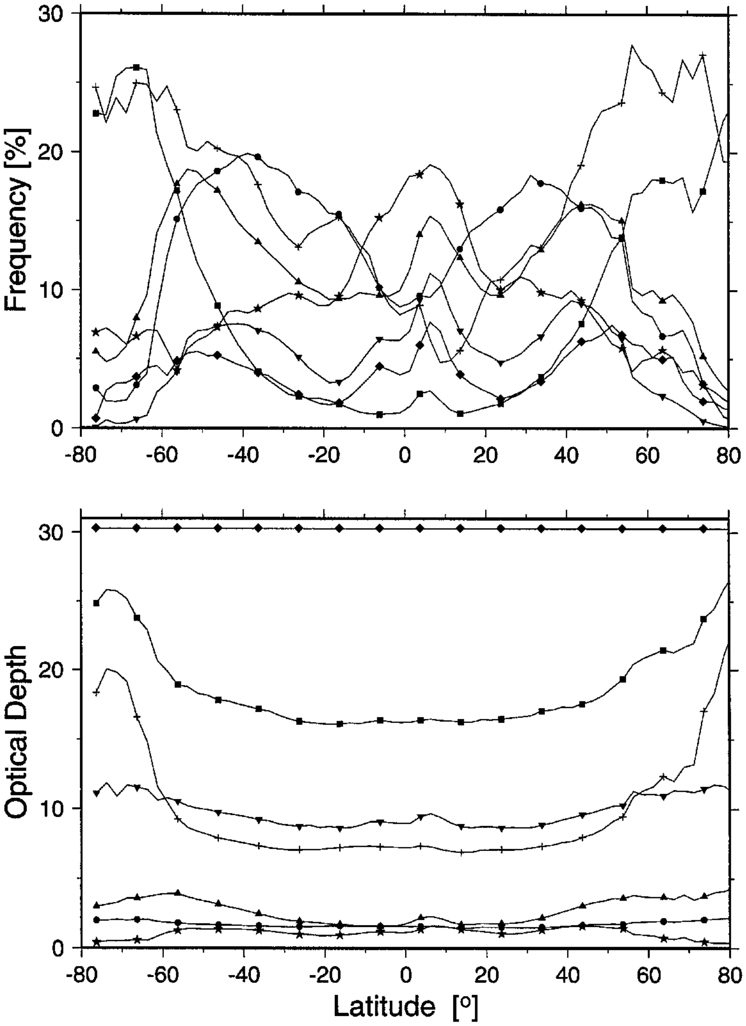

Figure 2.3 Zonal distribution of cloud types (top) and optical depths (bottom) over oceans as derived from ISCCP-C1 data; (●) cumulus, (+) stratus, (⟑) altocumulus, (■) nimbostratus, (★) cirrus, (⋎) cirrostratus, and (◆) deep convective clouds.

covered because of precipitation or wet ice conditions. A disadvantage of the passive microwave methods is their rather coarse horizontal resolution of a few tens of kilometers. Higher resolution can be achieved with infrared and visible imagery in cloud-free areas as obtained from AVHRR and the Landsat-Thematic Mapper, with resolutions of 1–5 km and 30–100 m respectively (Emery et al., 1991b; Steffen and Schweiger, 1991; Martin, 1993). SAR (Synthetic Aperture Radar) measurements allow an all-weather monitoring of sea ice with a resolution of 10 m. However, the coverage of large areas is hardly achieved by SAR or the Thematic Mapper because of the narrow swath widths of about 100 km and 185 km, respectively, compared with the separation of adjacent orbits of up to 1400 km in polar regions.

The interaction of wind and oceanic currents with the sea ice can cause strong migrations of the marginal ice zone and alter the sea ice coverage which is reflected in the plankton and particle concentrations in the near surface water. Dense phytoplankton blooms have been found below sea ice where they were not grown and clear, almost phytoplankton-free water has been observed in the open water adjacent to the ice edge where one would have expected phytoplankton blooms. Tracking of sea ice movement with the aid of successive AVHRR images allows identification of areas with such unexpected distributions of phytoplankton (Emery et al., 1986, Emery et al., 1991a).

Recently, Garrity (1992) has shown that utilization of microwave radiometry allows characterization of the depth, wetness, and stratification of the snow pack on floating ice. This information also could be used for computation of the radiation field below the sea ice.

Precipitation over the ocean can drastically change the salinity of the near surface water body within short time periods. Thus, precipitation can directly alter the environment of phytoplankton. Satellite measurements of precipitation reaching the surface, however, are largely indirect. Only during light rain is the microwave radiation interacting with rain drops transmitted to the top of the atmosphere (Wilheit et al., 1977). For moderate and heavy precipitation one has to measure the rain conditions at higher atmospheric levels or to observe the brightness of clouds in order to draw conclusions on the surface rain rates (Spencer et al., 1989). The latter technique is used at infrared wavelengths, too, as demonstrated by Arkin and Meisner (1987). Methods utilizing passive microwave measurements combining direct and indirect observations have been developed and successfully applied to SSM/I measurements over the global ocean (Bauer and Schlüssel, 1993). Plate 2.2 shows the monthly average rainfall over the sea for five months in the time period August 1987 through August 1988 as derived from SSM/I measurements. The strong seasonal and regional variation covers a range from no precipitation in subtropical areas to maxima greater than 1000 mm in the tropical convergence zone. The images also reveal the strong interannual variation. In August 1987 the tropical rainfall was higher than in August 1988 while the precipitation in the storm tracks in the middle latitudes of both hemispheres was less pronounced. This was likely to be an effect of the El Niño 1987. The application shown demonstrates that the use of climatological mean values instead of actual observations of precipitation certainly would lead to wrong estimates of local rainfall.

2.3 QUANTITIES DRIVING THE VERTICAL EXCHANGE IN THE UPPER OCEAN

The wind dynamically couples the atmosphere to the ocean. While acting on the sea surface the wind transfers momentum from the atmosphere to the ocean which leads to the formation of oceanic currents and to vertical mixing of the near-surface water. The vertical mixing determines the transport of particles from the upper waters to the deep sea. Remote sensing of the near-surface wind speed is achieved by observing the emissivity changes or variations of the radar backscatter of the wind-roughened sea surface. A variety of retrieval schemes have been developed for the use with passive and active satellite measurements. (e.g., Miller et al., 1982; Wentz et al., 1986; Guymer et al., 1981; Wentz et al., 1984). So far the techniques rely on semi-empirical approaches relating wind speed to emissivity changes (Pandey and Kakar, 1982). Theories based on first principles which can describe the relationships between wind and surface optical parameters are still premature for use with remote sensing methods.

The flight of the SSM/I, a well calibrated in-flight microwave radiometer, allowed for the first time retrieval of surface wind speeds with an accuracy better than 2 m s^{-1} when compared to co-located in-situ measurements (Goodberlet et al., 1989; Schlüssel and Luthardt, 1991). Monthly mean oceanic wind speeds derived from SSM/I measurements are shown in Plate 2.3 for five months as in Plate 2.2. Highest values of wind speed are found, as expected, in the Southern Ocean with means up to 15 m s^{-1}. A strong variability, related to the monsoon circulation, is seen in the northern Indian Ocean with lowest values near 1 m s^{-1} in November and February and highest wind speeds in the Somali or Findlater Jet showing wind speeds greater than 10 m s^{-1} in August 1988. According to Figure 2.2 the wind-speed fields are available almost daily in most regions which allows not only for the computation of monthly average fields but also for detailed process studies.

The existence of sea ice strongly affects the momentum exchange at the sea surface and, hence, the vertical mixing. Knowledge of the ice type and extent is necessary to delineate areas with decreased mixing in order to study details of the oceanic particle flux.

Precipitation also might affect the vertical mixing in the upper ocean in two ways. The momentum transferred by falling rain drops impinging on the surface causes vertical mixing of the uppermost layer of the ocean (Guymer et al., 1981). On the other hand, fresh rain water is less dense than sea water, hence, the precipitation leads to a stabilized upper ocean with reduced vertical mixing (Ostapoff et al., 1973). While the density stratification can cover the uppermost ten meters after a heavy rainfall, that lasts for several hours, it seems that this effect is more important than the mixing induced by the impact of drops on the sea surface. Therefore, the joint observation of precipitation and surface wind speed with passive microwave measurements is indicated when the particle flux in the uppermost ocean is studied.

2.4 PARAMETERS RELEVANT TO TRANSPORT AND DEPOSITION OF LITHOGENIC PARTICLES

The long-range transport of lithogenic particles from the continents to the ocean is effected by the three-dimensional atmospheric wind-vector field and its temporal evolution which determines the trajectories along which the particles are carried from their originating areas. Currently, there are no satellite instruments available which allow the complete measurement of the atmospheric wind field. Tracking of clouds and water-vapor structures in successive images from geostationary satellites allows the determination of wind vectors at single levels (Leese et al., 1971; Endlich and Wolf, 1981; Eigenwillig and Fischer, 1982). These satellite winds are useful in areas where no other measurements are available, but, they do not give a complete coverage. The thermal wind which is the vertical variation of the geostrophic wind due to horizontal temperature gradients can be obtained from temperature profiles retrieved from the TIROS (Television Infra Red Observational Satellite) Operational Vertical Sounder (TOVS) which is flown operationally on the NOAA spacecraft. Chedin et al. (1985) have demonstrated the retrieval of three-dimensional fields of the thermal wind from such temperature soundings. Although the thermal wind is the major component of the wind field in the upper troposphere an absolute wind field at an arbitrary level has to be known in order to calculate the complete wind field. This can currently only be achieved with the help of other observations and numerical weather forecast models.

The deposition of lithogenic particles on to the sea surface is most effectively done by precipitation processes. Thus, the observation of rain events must accompany the study of trajectories carrying the aerosols.

2.5 FUTURE PERSPECTIVES

Observations from space provide extensive global data that can be used to study meteorological parameters relevant to the oceanic particle flux. These data are the only source of information about large parts of the global atmosphere and ocean. Interdisciplinary research within the earth sciences has begun to exploit these data in order to understand coupled processes among atmosphere, ocean and cryosphere. Within the next decade the current operational Earth observation satellites will be amended and replaced by a series of orbiters carrying advanced as well as newly developed instruments which inter alia will be of great benefit for particle flux studies. An overview has been given by Dozier (1994). Obviously, the key instruments related to oceanic particle flux will be those directly dedicated to the marine biogeochemistry. However, instruments observing the atmosphere and the sea surface are complementary to those and the synergistic use of all data will certainly provide the most valuable insight.

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