Introduction to special section: Results of the *Meteor* 55: Tropical SOLAS Expedition

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[1] This special section presents results from an interdisciplinary research cruise to the northern tropical Atlantic Ocean, which took place in October–November 2002. The cruise was planned as a pilot study for the international Surface Ocean – Lower Atmosphere Study (SOLAS) project. This introduction summarizes the goals as well as the hydrographic and atmospheric setting of the expedition. We also present a brief review of the findings published in this section and elsewhere concerning controls on trace gas fluxes and the biogeochemical significance of dust composition and deposition. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 4820 Oceanography: Biological and Chemical: Gases; 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 4875 Oceanography: Biological and Chemical: Trace elements. **Citation:** Wallace, D. W. R., and H. W. Bange (2004), Introduction to special section: Results of the *Meteor* 55: Tropical SOLAS Expedition, *Geophys. Res. Lett.*, *31*, L23S01, doi:10.1029/2004GL021014.

1. Introduction

[2] This Special Section of Geophysical Research Letters is a collection of 8 papers based on results of the 55th expedition of the German research vessel *Meteor* (M55). The expedition focused on biogeochemical interactions between the surface ocean and atmosphere within the tropical North Atlantic, and was planned as a national demonstration project for the Surface Ocean Lower Atmosphere Study (SOLAS). SOLAS (www.solas-int.org) is a relatively new international global change research initiative that has as its goal:

> "To achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and how this coupled system affects and is affected by climate and environmental change".

The expedition comprised a trans-Atlantic section from west to east along 10–11°N together with a short, mid-ocean north-south transect to the equator (graphical representations of the cruise track are presented in the individual papers).

[3] The tropical North Atlantic was chosen for the demonstration project because: (1) biological impacts of dust deposition should be readily detectable along a strong east-west gradient in deposition that exists in the region; (2) previous meridional surveys had shown the region to be significant for the production of important halogenated trace gases; (3) the proximity of the Inter-Tropical Convergence Zone (ITCZ) allowed for sampling of trace gases and aerosols in air masses with varying back-trajectories and hence exposure to varying oceanographic conditions. The north-south transect allowed for study of air-sea exchanges in the equatorial upwelling and for sampling of atmospheric parameters across the ITCZ.

[4] The main objectives were to: (A) characterize the distribution of the air-sea flux of trace gases and investigate within-ocean mechanisms that determine these fluxes and (B) investigate aerosol chemistry, aerosol (dust) deposition, and associated within-ocean biogeochemical consequences in a region of high (and variable) dust deposition. In particular, we were interested in examining the hypothesized relationship between dust-derived iron supply and nitrogen fixation [*Falkowski*, 1997]. With these overall goals in mind, the following activities were conducted:

[5] 1. Characterization of trace gas distributions within the atmosphere and tropical surface waters and experimental study of production-degradation pathways in surface waters. The trace gases included sulfur-containing gases, naturally produced halocarbons including reactive species such as BrO, alkyl nitrates, and oxygenated organic compounds.

[6] 2. Determination of the distribution patterns of phytoplankton biomass and photochemically produced compounds as potential producers of trace gases.

[7] 3. Chemical characterization of atmospheric aerosols for halogen, trace metal and nitrogen content. Assessment of the chemical behavior of such aerosols following deposition to ocean waters.

[8] 4. Measurement of trace metals (e.g., Fe) and their speciation in surface water and shallow vertical profiles in relation to atmospheric and sub-surface inputs, phytoplankton composition and remineralization.

[9] 5. Investigation of the mixed layer nitrogen cycle with an emphasis on nitrogen fixation.

[10] 6. Bioassays and molecular biological studies to determine nutrient and/or trace metal limitation (e.g., N, P, Si, Fe, other metals). Physiological studies of photosynthetic organisms along strong gradients of nutrient limitation.

[11] Results from these activities are presented in this special section [*Baker*, 2004; *Croot et al.*, 2004a, 2004b; *Quack et al.*, 2004; *Richter and Wallace*, 2004; *Voss et al.*, 2004; *Walter et al.*, 2004; *Williams et al.*, 2004], and in several papers published elsewhere [*Gros et al.*, 2004; *Körtzinger*, 2003; *Mills et al.*, 2004]. In this introduction,

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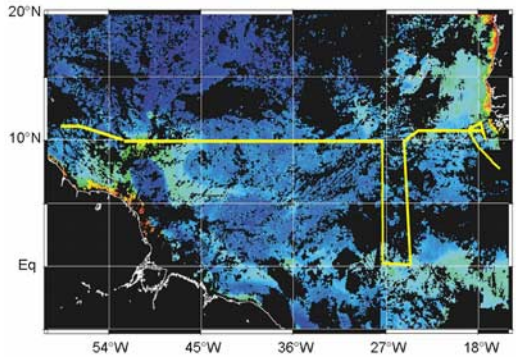

Figure 1. Cruise track for *Meteor* 55 (12 October to 17 November 2002) superimposed on a SeaWiFS composite image of phytoplankton pigment concentration in the range from 0.1 mg m^{-3} (blue) to 10 mg m^{-3} (red) for October 2002 (http://seawifs.gsfc.nasa.gov).

we provide background information relevant to the papers in the special section, as well as an assessment of what was learned from the demonstration project.

2. Oceanographic and Atmospheric Setting

2.1. Ocean

[12] Several of the main hydrographic features of the tropical Atlantic [see, e.g., *Schott et al.*, 2004; *Snowden and Molinari*, 2003] are visible in a composite Sea-viewing Wide field-of-view Sensor (SeaWiFS) ocean color image for the time of the cruise (Figure 1). With respect to horizontal circulation, the Meteor 55 cruise was located primarily to the north of the eastward-flowing North Equatorial Counter Current (NECC). In the western part of the section, the cruise track intersected high chlorophyll water visible by satellite at about 52°W (Figure 1). The high chlorophyll was associated with Amazon Plume water of low salinity (S > 30) that had been retroflected from the North Brazil Current and was being fed into the NECC [*Körtzinger*, 2003]. Patches of this low salinity water were encountered further east to 32°W, likely associated with northward meandering of the NECC. Two main regions of upwelling were crossed: (1) the mid-cruise southward detour to the equator allowed for sampling of upwelled water there. SeaWiFS imagery indicates that the upwelling was most pronounced within 1–2° of the equator; (2) the Guinea Dome, a cyclonic circulation feature with open-ocean upwelling which is usually centered between 9°N 25°W and 10.5°N 22°W [*Siedler et al.*, 1992] or at 12°N 25°W according to *Snowden and Molinari* [2003]. The Dome was however not clearly identifiable in our data, or in the SeaWiFS imagery. In general, the upwelling is part of a shallow overturning circulation typical of the tropical oceans, and that is fed by water subducted in the sub-tropics of both the northern and southern hemispheres.

[13] The nutrient and oxygen sections (Figure 2) showed the shoaling of the nutricline from west to east and a significant difference in dissolved oxygen concentrations between the western and eastern basins. The shoaling of the nutricline is associated with steepening of the thermocline towards the east. Temperature gradients as steep as 0.5°C m^{-1} were observed immediately below the mixed layer in the eastern half of the section. Close to the equator, within the region of equatorial upwelling, isothermal and isohaline layers were observed extending as deep as 75 m, although dissolved oxygen was 'well-mixed' only to about 50 m.

[14] The low oxygen concentrations (and higher nutrient levels) of the sub-surface eastern basin are associated with weak renewal of the South Atlantic Central Water. The main oxygen minimum was found at depths of 400–500 m (Figure 2) however a less-pronounced oxygen minimum was also found in the eastern basin at the base of the thermocline (depths of 60–150 m; $26.3 < \sigma_\Theta < 26.5$).

2.2. Atmosphere

[15] The atmospheric setting of the cruise was dominated by meandering of the ITCZ, which meant that air masses sampled along the cruise track had origins in both the northern and southern hemispheres. Four-day, sea surface level, air mass back trajectories (computed by the German Weather Service, Offenbach, Germany) indicated that air masses sampled at 10°N mainly originated in the northern hemisphere (15–18 October, 20, 23–25 October, 2–9 November) (Figure 3). During the days 19, 21–22 October, however, southern hemisphere air masses were also found at 10°N. Air masses sampled south

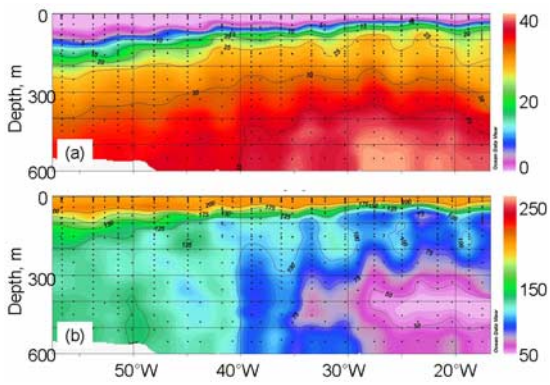

Figure 2. Concentrations of (a) nitrate (μmol L^{-1}) and (b) oxygen (μmol L^{-1}) along the main west–east transect at 10–11°N. Dots mark the sample depths.

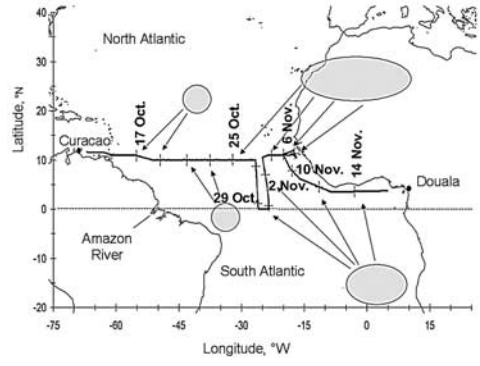

Figure 3. *Meteor* 55 cruise track with major source areas of air masses indicated (shaded). Source areas were identified based on four-days air mass back trajectories provided by the German Weather Service, Offenbach, Germany.

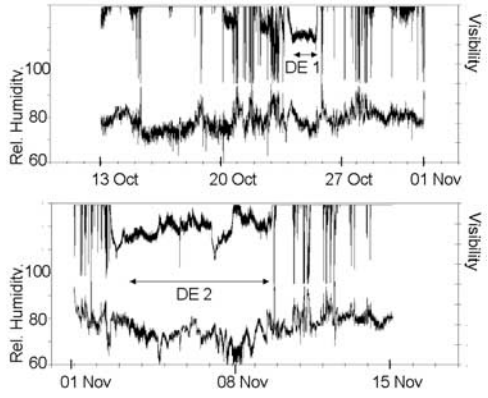

Figure 4. Relative humidity and visibility (arbitrary units) during M55. DE1 and DE2 mark the major dust deposition events.

of 7°N generally originated in the southern hemisphere (26 October–1 November, 10–15 November) (Figure 3). Air masses sampled at any location east of 24°W and north of 7°N (2–9 November) originated in the northwestern Saharan region. The analysis of atmospheric carbon monoxide and propane concentrations as tracers for atmospheric pollution events [*Gros et al.*, 2004] revealed that during the first days (15–23 October), pristine North and South Atlantic air was sampled, whereas pollution events were recorded occasionally during the rest of the cruise. Identified pollution sources were biomass burning emissions from equatorial and southern Africa as well as industrial emissions from northern Africa.

[16] As expected for the region, strong rain showers and dust deposition were encountered. Visibility and relative humidity data from the ship's continuous record were found to be useful in identifying these events (Figure 4). Major rain showers, identified by lowered visibility and enhanced relative humidity, were observed several times: 18–19 October, 21–24 October, 28–29 October, and 11–13 November (Figure 4). Dust deposition events were identified by lowered visibility and decreased relative humidity. Major dust deposition events (DE) occurred around 25 October and in the period from 3 to 10 November when sailing close to the coast of Africa (Figure 4). As indicated by the air mass back trajectories the major source region for the dust was the western Sahara (Figure 3).

3. Major Findings

3.1. Trace Gas Production and Flux

[17] The sampling program addressed the air-sea flux of several compounds of importance for the Earth's radiative budget (CO_2, N_2O, dimethyl sulphide) and the chemistry of the atmosphere ($CHBr_3$, CH_3I, acetone, methanol, acetonitrile). The results highlighted the diverse factors that determine the flux of different compounds.

[18] *Körtzinger* [2003] observed that Amazon plume surface water acts as a significant sink for atmospheric CO_2. The low pCO_2 of these waters was attributed to a sequence of processes operating remotely in the lower reaches of the river (outgassing), the estuary (mixing with alkaline seawater), and the low-salinity plume over the South American shelf (nutrient-fuelled biological carbon drawdown after turbidity reduction). While plausible, it is notable that there are presently no inorganic carbon and pCO_2 data available from the critical nearshore regions with which the explanation can be validated.

[19] A study of bromoform ($CHBr_3$) distributions [*Quack et al.*, 2004] demonstrated the utility of combining atmospheric measurements with sub-surface vertical profile measurements in order to identify processes controlling air-sea fluxes. The Amazon Plume was found to have extremely high subsurface $CHBr_3$ concentrations but a relatively low sea-to-air flux due to strong salinity stratification, which prevented contact of the subsurface maximum with the atmosphere. Despite a widespread subsurface $CHBr_3$ maximum a strong sea-to-air flux was observed only in the Equatorial upwelling region. This suggests that $CHBr_3$ production may be associated with subsurface biological processes, including perhaps the decay of blooms (cf. Amazon plume), but that physical upwelling determines the location and strength of the sea-to-air flux. High levels of $CHBr_3$ measured in air masses that had transited the African coast were hypothesized to be associated with strong coastal upwelling but this remains to be tested with field data.

[20] Measurements of surface and subsurface dissolved N_2O also highlighted the importance of upwelling, with enhanced surface water concentrations and hence sea-to-air fluxes being found at the equator, at the Guinea Dome and over the continental shelf off West Africa [*Walter et al.*, 2004]. Despite these regional hotspots, the tropical North Atlantic was, overall, only a weak net source of N_2O to the atmosphere.

[21] In contrast, the CH_3I sea-to-air flux was relatively large throughout the region [*Richter and Wallace*, 2004]. Incubation experiments supported prior suggestions that a primary CH_3I source is an abiotic, light-dependent pathway that may also be dependent on the concentration of filterable organic precursors. A mass balance suggested that surface supersaturation reflects a balance between this light-dependent abiotic production and the wind-speed dependent sea-to-air flux. Measurements of vertical profiles showed that CH_3I was undetectable below about 100 m (A. Chuck, personal communication). In contrast, vertical profiles of another photochemically produced species, H_2O_2 [*Croot et al.*, 2004b], show slightly deeper penetration (to approx. 125 m) which may be indicative of an additional subsurface, 'dark biological production' of H_2O_2 at or close to the chlorophyll maximum.

[22] Finally *Williams et al.* [2004] reported some of the very first simultaneous measurements of both the atmospheric and the water concentrations of acetone, methanol, and acetonitrile. Air-sea flux densities were highly variable along the section, indicating both uptake and release from/to the ocean. The average flux densities implied that the tropical Atlantic Ocean might act as a net source for acetone and acetonitrile and a net sink for methanol, at least during the season studied. The first reported depth profiles of these compounds were suggestive of relatively slow sub-surface degradation for acetonitrile and methanol.

[23] The trace gas studies emphasized the utility of subsurface vertical profiles and studies of within-ocean production/degradation mechanisms, in addition to simply

measuring atmosphere-ocean saturation anomalies, in order to gain insight into variability of atmosphere-ocean fluxes.

3.2. Aerosols and Their Biogeochemical Impact

[24] The other principle theme was investigation of the chemical composition of the atmospheric aerosol and the effect of aerosol (dust) deposition on surface layer chemistry and biology. *Baker* [2004] investigated soluble iodine and its speciation in size-fractionated aerosol samples. The highest levels were found in aerosol sampled off the West coast of Africa and were hypothesized to originate with iodocarbon emissions from the West African upwelling. The iodine speciation data were some of the first of their kind, and appear to be inconsistent with current models of reactive iodine chemistry. Notably, IO_3^-/I^- ratios were very low in Southern Hemisphere air, contrary to the expectation that IO_3^- should accumulate as the aerosol 'ages'. This points either to potential problems with model chemistry or, alternatively, there may be major differences in the iodine source distributions for the Northern and Southern hemisphere aerosol.

[25] The eastern tropical North Atlantic is one of the major regions of dust deposition for the world ocean. Surface waters of the region are low in macronutrients, so dust-derived Fe is not expected to stimulate carbon fixation. Rather, we addressed the hypothesis [*Falkowski*, 1997] that dust-derived Fe limits nitrogen fixation. This hypothesis was supported both experimentally using shipboard incubation experiments [*Mills et al.*, 2004] and also via very clear correlations along the cruise track of dust deposition, water column Fe inventories [*Croot et al.*, 2004a] and measured nitrogen fixation rates [*Voss et al.*, 2004]. Some key findings included the suggestion that water-column dissolved Fe concentrations at the eastern end of the section are effectively 'saturated' by the massive dust inputs. The incubation experiments, on the other hand, suggested that N-fixation was co-limited by both Fe and P, and that dust might supply both of these limiting elements. The latter suggestion is controversial but important, and requires further experimental investigation. Taken together, the studies present some of the most convincing evidence to-date that dust deposition 'fuels' nitrogen fixation. Significantly, Fe appears to be limiting for this process even in a region subject to some of the world's highest (and also most variable) dust inputs.

[26] **Acknowledgments.** We are indebted to all participants of M55 and many other colleagues for their excellent collaboration without which M55 would not have been successful. We thank P. Fritsche and F. Malien for the nutrient and O_2 measurements; H. P. Hansen and J. Schafstall for the CTD measurements; J. Herrmann for data management; and two anonymous reviewers for their valuable comments. We acknowledge the support by the officers and crew of R/V *Meteor*, and the German Weather Service. We thank the authorities of Guinea-Bissau for permission to work in their economic zone. The expedition was financially supported by the *Deutsche Forschungsgemeinschaft* through grant WA 1434/3 under the *Meteor Schwerpunktprogramm*.

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