CHAPTER 53

EFFECTS OF THE GULF STREAM ON WIND WAVES IN SWADE

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ABSTRACT

Preliminary results of a numerical study of wave-current interactions in SWADE for 20 Oct. 1990 to 31 Oct. 1990 are presented. The results are obtained with the wave model WAVEWATCH, which incorporates both wave-current interactions and a full description of the dynamics wave growth and decay. It is shown that wave-current interactions are expected to be sufficiently strong to be observed in mean wave parameters, but that significant effects of interactions occur close to the Gulf Stream only. Furthermore, wave growth and decay are strongly influenced by the currents. Thus, modelling of wave-current interactions on the scales considered requires a comprehensive assessment of both (conservative) wave-current interactions and of the dynamics of wave growth and decay.

1 Introduction

Effects of the Gulf Stream on wind waves are assessed in the light of the Surface Wave Dynamics Experiment (SWADE, Weller et al. 1991). This experiment took place during the winter 1990-1991 on the continental shelf at the East coast of the United States, north of Cape Hatteras. Due to the vicinity of the Gulf Stream (the Gulf Stream actually intruded into the measurement array in early March 1991), wave-current interactions are potentially important in analyzing experimental data. Furthermore, the SWADE data provides a unique opportunity to verify wave-current interaction models due to the above intrusion.

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The wave-current interaction studies within SWADE consist of two parts. First, a mainly numerical assessment of wave-current interactions is made for the first Intensive Observation Period (IOP) of October 20 through 31 1990. The objective is to estimate effects of a realistic Gulf Stream on ocean wind waves using a full third-generation ocean wave model to provide a synthesis of all the idealized wave-current interaction studies performed so far. Such a study is the logical extension of Holthuijsen and Tolman (1990, 1991; henceforth denoted as HT). Secondly, an intercomparison of observations and model hindcasts will be made for part of the third IOP (March 3 through 5, 1991). The objective is to assess and verify present insights in wave-current interactions. In the present paper, preliminary results for the first part of the SWADE wave-current interaction studies will be presented.

2 Models

A cascade of nested models with increasing spatial resolution has been used, consisting of an Atlantic basin model (1°×1° longitude-latitude resolution), a regional model ($^1/_4$°×$^1/_4$°) and the so-called SWADE model ($^1/_{12}$°×$^1/_{12}$°) (see Weller et al. 1991, Fig. 11 and present Fig. 1). The Atlantic basin model is primarily used to provide boundary conditions for the regional model, and does not include currents. Because winds and waves outside the regional model proved irrelevant for the period considered, the Atlantic basin will not be considered in the following discussions. Gulf Stream surface currents for the regional and SWADE models (see Fig. 1) are obtained from feature models and the operational surface temperature analysis of NOAA/NMC. Wind fields for both models consist of high resolution SWADE wind analyses.

The results presented in this paper are obtained with the latest version of the model WAVEWATCH (Tolman 1991, 1992, 1993). In this model, the evolution of the action density spectrum $N(\omega,\theta,\phi,\lambda,t)$ is calculated, where ω is the absolute wave frequency (as observed in a fixed frame of reference), θ is the wave direction, ϕ is the latitude, λ is the longitude and t is the time. The action density spectrum N is directly related to the energy or variance density spectrum $F(\omega,\theta,\phi,\lambda,t)$, $N = F/\sigma$ (for brevity of notation dropping the dependence of N and F on ω, θ, ϕ, λ and t), where σ is the intrinsic or relative frequency, as observed in a frame of reference moving with the mean current. The frequencies σ and ω, the wavenumber vector $\mathbf{k}$, the depth d and the current velocity U are interrelated in the combined Doppler-dispersion relation

$$\sigma = \sqrt{gk \tanh kd} = \omega - \mathbf{k}\cdot\mathbf{U} \ . \tag{1}$$

The balance equation for the action density spectrum N becomes (e.g., WAMDI group 1988, Tolman 1991):

$$\frac{\partial N}{\partial t} + (\cos\phi)^{-1}\frac{\partial}{\partial\phi}[c_\phi \cos\phi\ N] + \frac{\partial}{\partial\lambda}[c_\lambda N] + \frac{\partial}{\partial\omega}[c_\omega N] + \frac{\partial}{\partial\theta}[c_\theta N] = S \ , \quad (2)$$

where $c_\phi = \mathrm{d}\phi/\mathrm{d}t$ etc. are the propagation velocities in the corresponding spaces (e.g., WAMDI group 1988, Tolman 1991), and where S denotes the net source term. The source term S consists of wind input (Janssen, 1989, 1991), nonlinear wave-wave interactions (Hasselmann and Hasselmann, 1985), energy dissipation due to whitecapping (Janssen, 1991) and energy dissipation due to bottom friction (Hasselmann et al., 1973). Thus, the present source terms are equivalent to those of cycle 4 of the WAM model (see, e.g., Mastenbroek et al., 1993). The source terms are corrected for effects of mean currents by applying them in a frame of reference moving with the mean current.

The numerics of WAVEWATCH as used in the present study incorporate a second order SHASTA propagation scheme and dynamic implicit source-term integration as described by Tolman (1992). The spectrum is discretized using 24 directions ($\Delta\theta = 15°$) and 33 frequencies (0.042 Hz through 0.88 Hz, $f_{i+1} = 1.1 f_i$). The time steps Δt are 450 s for the regional model and 240 s for the SWADE model.

In the final presentation of this part of the SWADE wave-current interaction studies, results of the WAM model (WAMDI Group, 1988) will also be included. These results are presently obtained by S. Hasselmann, H.C. Graber and R.E. Jenssen. Note that cycle 4 of WAM (spring 1992) incorporates wave-current interactions for steady currents.

3 Meteorological conditions

On Oct. 20, winds in the regional model are weak with predominantly northeasterly directions, except for a fairly strong depression, which moves rapidly eastward over Nova Scotia. For the next few days, the entire region has weak northeasterly winds. On Oct. 24 a small depression develops over Cape Hatteras and starts moving in a northeasterly direction. On Oct. 25, this system is located south of Nova Scotia and on Oct. 26 it has left the regional model area. On the same day several systems develop around Cape Hatteras. These systems merge into a complex structure with strong northeasterly, northwesterly and southwesterly winds in the northwest, southwest and southeast quadrants respectively (wind speeds over 20 m/s). In the next two days this systems moves in a northeasterly direction and at Oct. 29 this system has left the regional model. Finally, on this day a cold air outbreak occurs north of Cape Hatteras, and the associated depression moves over Nova Scotia on Oct 31.

4 Results

Model calculations have been performed for the period of Oct. 15 1990 through Oct 31, 1990. The period of Oct 15 through Oct 20, 0000 UTC is used to initialize the models. For both the regional model and the SWADE model calculations have been performed with and without the Gulf Stream. Thus, effects of the Gulf Stream can be isolated by simply taking the difference between the two model runs. All weather systems described in section 3 are accompanied by a distinct wind sea system. Furthermore, all these systems generate swell traveling in northerly to easterly directions. The complicated structure on Oct 26 through 28, also radiates swell energy in southern directions.

Effects of wave-current interactions are found to vary on small space and time scales. This is illustrated in Fig. 2 with the maximum and minimum current-induced modulation of the significant wave height H_s and the mean wave length L for several models and areas.

$$H_s = 4\sqrt{E} \quad , \quad E = \iint F(\omega,\theta)\, d\omega\, d\theta \ . \tag{3}$$

$$L = E \left(\iint 2\pi k^{-1} F(\omega,\theta)\, d\omega\, d\theta \right)^{-1} . \tag{4}$$

The time scale of pronounced features in this figure is typically several hours to several days. A comparison of results for the SWADE model (solid lines) and the corresponding area in the regional model (dashed lines) shows qualitatively similar results. Due to the fairly limited resolution of the region model (a cross section of the Gulf Stream consists of no more that five grid points), the regional model shows less detail (figures not presented here) and consequently slightly different but similar extreme values for ΔH_s and ΔL (see Fig. 2). Consequently, one might expect the regional model to give a fairly accurate estimate of the wave-current interactions, in spite of the relatively poor resolution. Furthermore, Fig. 2 shows only limited effects of wave-current interactions in the overall quiet periods of Oct 20 through 23, Oct 25 and Oct 29. This might be expected because the wave heights in this period are generally less than 2 m. Finally, Fig. 2 shows that the largest impacts of wave-current interactions occur outside the SWADE area on Oct. 27 and 28.

To assess effects of wave-current interactions in more detail, the spatial distribution of effects of wave-current interactions will be discussed in some detail for Oct. 28, 0000 UTC. This time has been selected for the interesting interactions in the model. Note that, as discussed above, this time is not representative for the entire period considered. The discussion will concentrate on results for the regional model, because this model is expected to be sufficiently accurate to show the general features of the present Gulf Stream current field. In Fig. 3 the significant wave height H_s' (obtained from a model including the Gulf Stream) and the current-induced modulation of the wave height ΔH_s (model differences) are presented. Similarly, Fig. 4 shows the mean absolute period T_a, Fig. 5 shows the integral input source term $S_{in,i}$ and Fig. 6 shows the integral dissipation (whitecapping) source term $S_{ds,i}$.

$$T_a = E\left(\iint 2\pi\omega^{-1}F(\omega,\theta)\,d\omega\,d\theta\right)^{-1} . \tag{5}$$

$$S_{in,i} = \iint S_{in}(\omega,\theta)\,d\omega\,d\theta \ . \tag{6}$$

$$S_{ds,i} = \iint |S_{ds}(\omega,\theta)|\,d\omega\,d\theta \ . \tag{7}$$

Figures 3 through 6 show that the space scales of current-induced modulations of the wave field are governed by the corresponding scales of the current and wind fields. Furthermore, such modulations are mostly confined to the immediate vicinity of the Gulf Stream and modulations can be large enough to be observed in the overall model results (i.e., without differencing models, figure panels a). However, it is nearly impossible to pinpoint the exact location of the Gulf Stream from such mean wave parameters only.

In the wave height and period fields presented in Figs. 3 and 4, several features can be observed.

First, swell trapping occurs south of Cape Hatteras. The trapped swell is identified by the significant increase of the wave height and the absolute period, which are closely confined to the Gulf Stream. The trapped swell was generated in the coastal area between Cape Hatteras and Cape Cod in the previous 36 hours. Note that the trapped swell is accompanied by a "shadow zone" just south of the Gulf Stream, as would be expected from straightforward energy conservation. Note furthermore the occurrence of two focal points of long wave energy on the coast south of Cape Hatteras (see Fig. 4). This current-induced modulation of swell energy around the Gulf Stream, and the location the Gulf Stream near the coast suggest that swell penetration at coast south of Cape Hatteras can be influenced significantly by Gulf Stream (unlike coastal waves in most other areas).

Secondly, the combined wind-wave and swell field east of 68°W shows a complicated impact of the currents. Note the apparent reflection of wave energy south of the meander at 39°N, 56°-60°W (Fig. 4). Given the predominant wave direction, such a reflection was expected from the results of HT for a straight section Gulf Stream. Furthermore, the meander at 42°N, 58°W shows an impact similar to that of a ring for swell as shown by many authors.

Finally, several small and fairly weak rings in the area between the above two areas all show a the typical signature of a ring for swell fields, although the impact is typically small. Note that the rings identify the locally dominant swell direction.

As discussed by HT indirect effects of currents on the dynamics of wave growth and decay are expected to be important on the scale of the Gulf Stream. For a separate ring, such effects are easily isolated, due to the closed-system nature of the ring. For a meandering Gulf Stream, effects of modified growth dynamics can occur simultaneously with reflection and trapping of waves. Thus an assessment of current-induced modulations of wave-growth dynamics requires a detailed analysis of individual spectra. In the present paper, only the potential of such effects will be established by assessing the integral source terms $S_{in,i}$ (Fig. 5) and $S_{ds,i}$ (Fig. 6). These figures show current-induced modulations of $S_{in,i}$ and $S_{ds,i}$ of 20% to 50%, which agrees well with the results of HT for a ring. Considering the importance of current-induced modulations of the dynamics of wave growth in the latter case, a similar importance is expected here. The Gulf Stream, however, does show differences compared to the corresponding idealized cases of HT. The current-induced modulations of the input source term (Fig. 5) are centered on the currents (as in HT). This might be explained from the fact that the input winds (relative to the current) and local (conservative) interactions show similar modulations. The dissipation, however, changes both in and outside the Gulf Stream. In particular in the above mentioned reflection zone (39°N, 56°-60°W) increased dissipation occurs at the edge of the Gulf Stream rather than at the center (in contrast to the results of HT).

One final remark should be made on the results of Figs. 3 through 6. The impacts of wave-current interactions as presented in these figures appear to occur mainly when the winds are decreasing, in other words, when the relative importance of wave growth decreases. This suggests that the dynamics of wave growth and decay dominate wave-curent interactions in active growth conditions, which is another indication for the importance of incorporating the dynamics of wave growth and decay when considering wave-current interactions at the present scales.

5 Preliminary conclusions

The above preliminary results for numerical simulation of wind waves on the Gulf Stream lead to the following preliminary conclusions.

- Wave-current interactions induced by the Gulf Stream are sufficiently strong to be identified in wave height and mean period, but do not necessarily pinpoint the exact location of the Gulf Stream.
- Space (and time) scales of effects of wave-current interactions are relatively small and are governed by the corresponding scales of the wind field and the Gulf Stream.
- Effects of wave-current interactions are mainly confined to Gulf Stream and its direct surroundings, in particular for regions with active wave generation. Effects away from the Gulf stream are usually related to swell propagation and generally of moderate magnitude.
- The model indicates that trapping of swell can occur in realistic conditions. South of Cape Hatteras this might significantly influence swell penetration at the coast.
- In active generation conditions an interplay between conservative wave-current interactions and the dynamics of wave growth and decay occurs. Such an interplay is neglected in virtually all other wave-current interaction studies.
- The spatial resolution of regional model appears to be sufficient to assess wave-current interaction features of the Gulf Stream. The SWADE model, however, is expected to be significantly more accurate due to the better resolution.

6 Outlook

As stated in the introduction, this paper presents preliminary results of SWADE wave-current interaction studies. For the first part of the SWADE wave-curent interaction study, the follwing work is inprogress.

- The interplay between dynamics and kinematics are analyzed in more detail both by intercomparing spectra and by analyzing evolution of the net effect of wave-current interactions in space and time.
- Effects of different physical and numerical approaches are assessed by intercomparing results of the models WAVEWATCH and WAM.
- An assessment of effects of wave-current interactions with regard to remote sensing is being considered.

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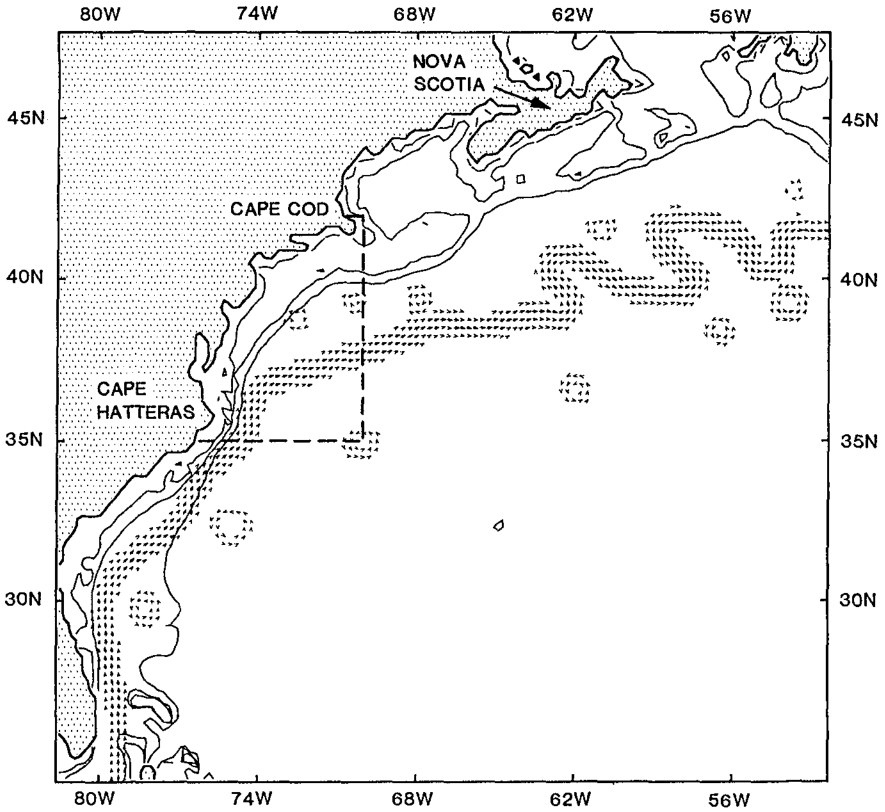

Fig. 1 Layout of the regional grid (entire figure) and SWADE grid (dashed lines). Depth contours for 25 m, 100 m and 1000 m. Vectors indicate location and direction of Gulf Stream (U > 0.5 m/s only, $U_{max} \approx 2$ m/s for the Gulf Stream and $U_{max} \approx 1$ m/s for a typical ring.

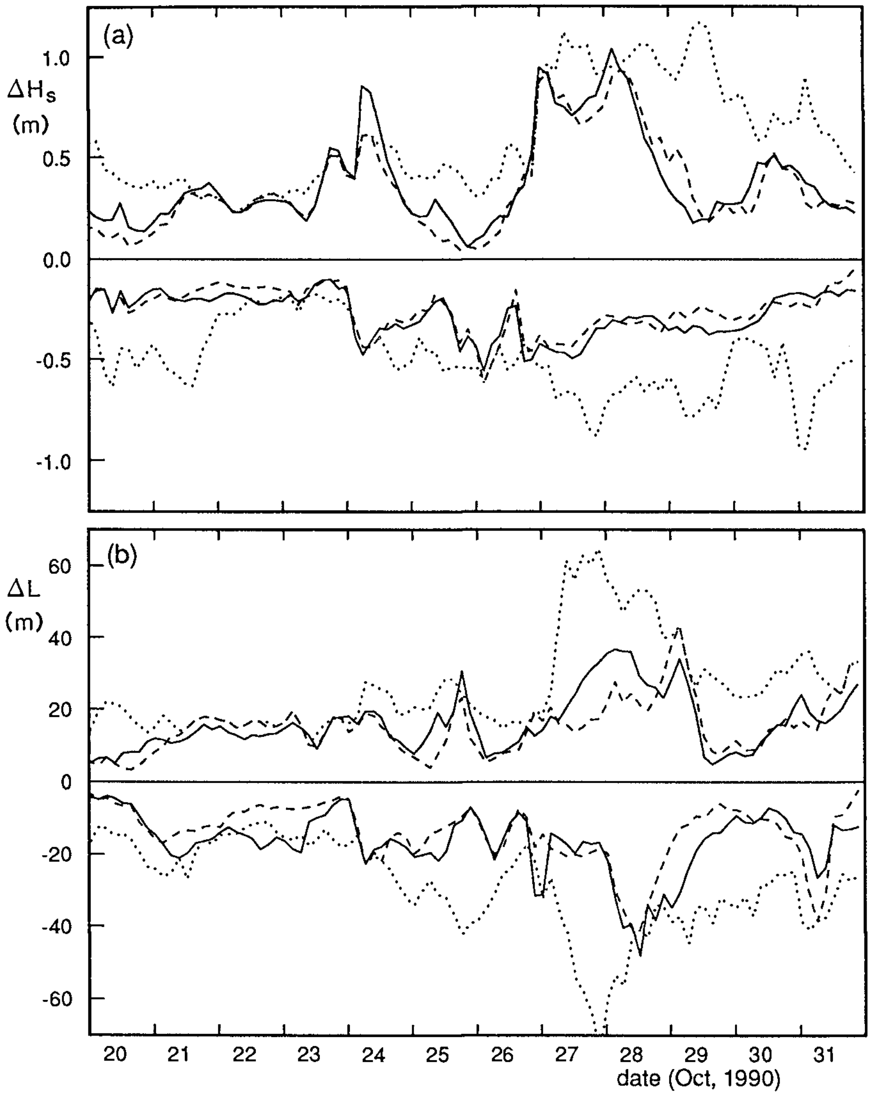

Fig. 2 Maximum and minimum current-induced modulation of the significant wave height (ΔH_s, panel a) and the mean wave length (ΔL, panel b) for the SWADE model (solid lines), the regional model (dotted lines) and the part of the regional model covering the SWADE model (dashed lines).

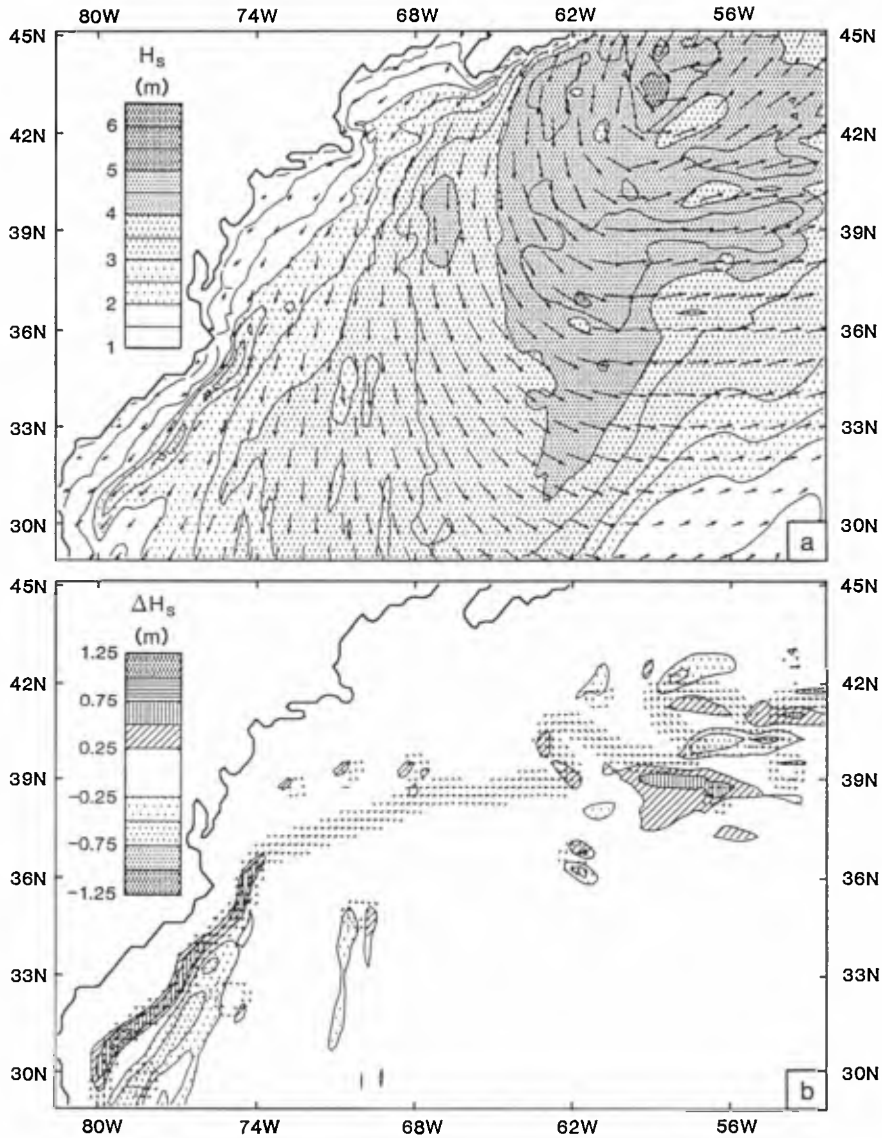

Fig. 3 The significant wave height (H_s, panel a), and its current-induced modulation (ΔH_s, panel b) for part of the regional model on Oct. 28, 0000 UTC.

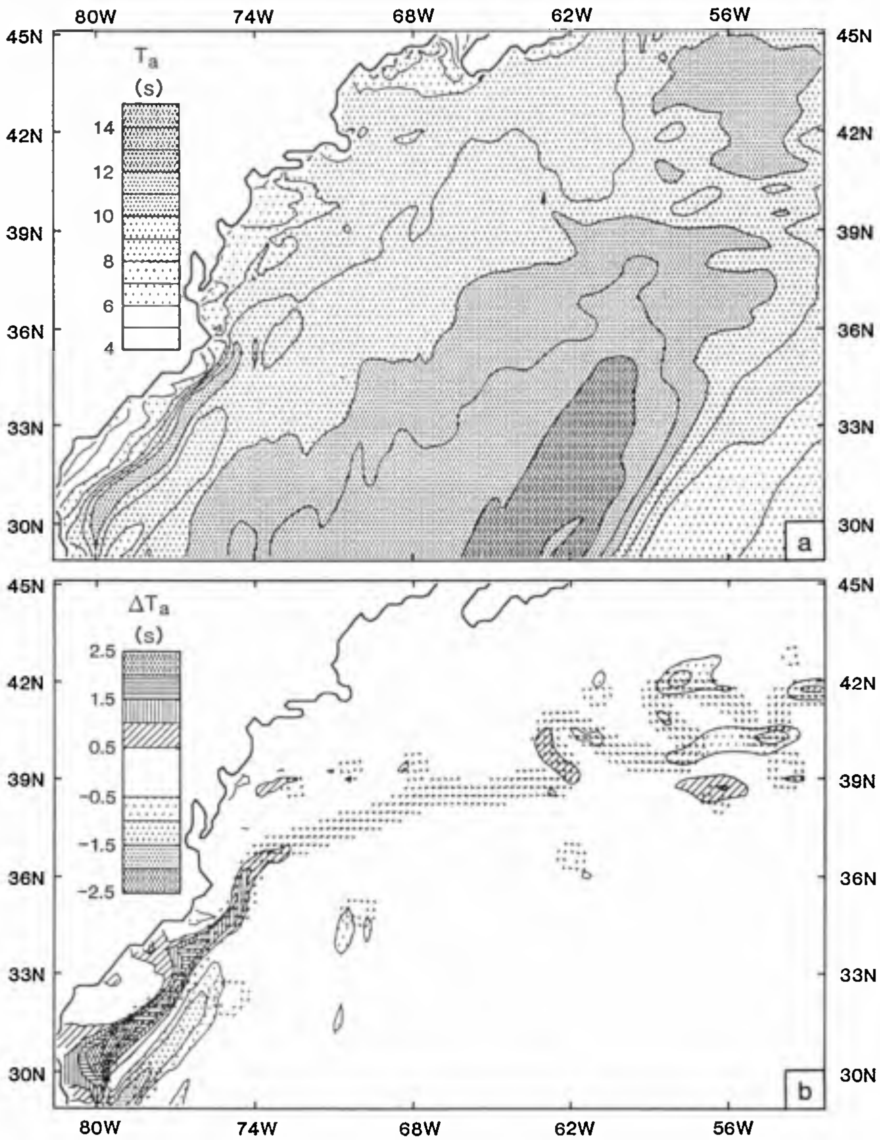

Fig. 4 Like Fig. 3 for the mean absolute wave period T_a.

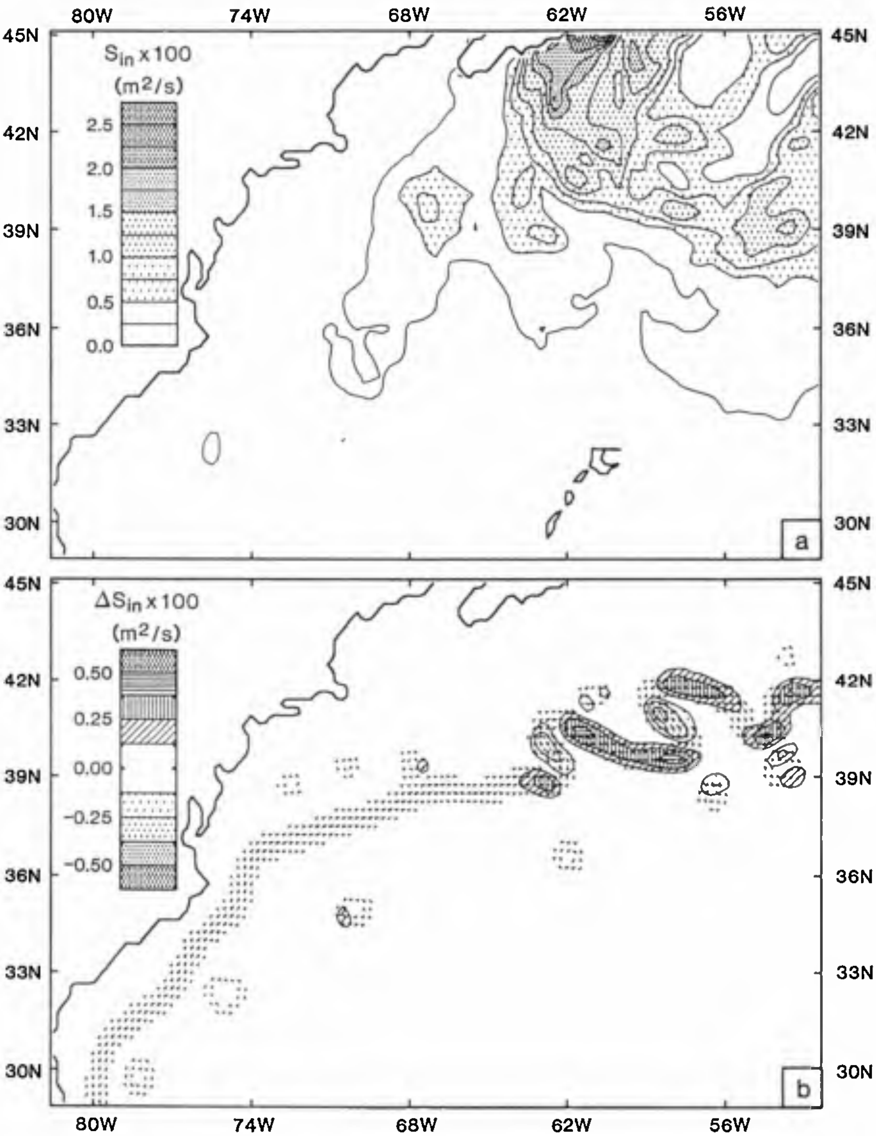

Fig. 5 Like Fig. 3 for integral input source term $S_{in,i}$.

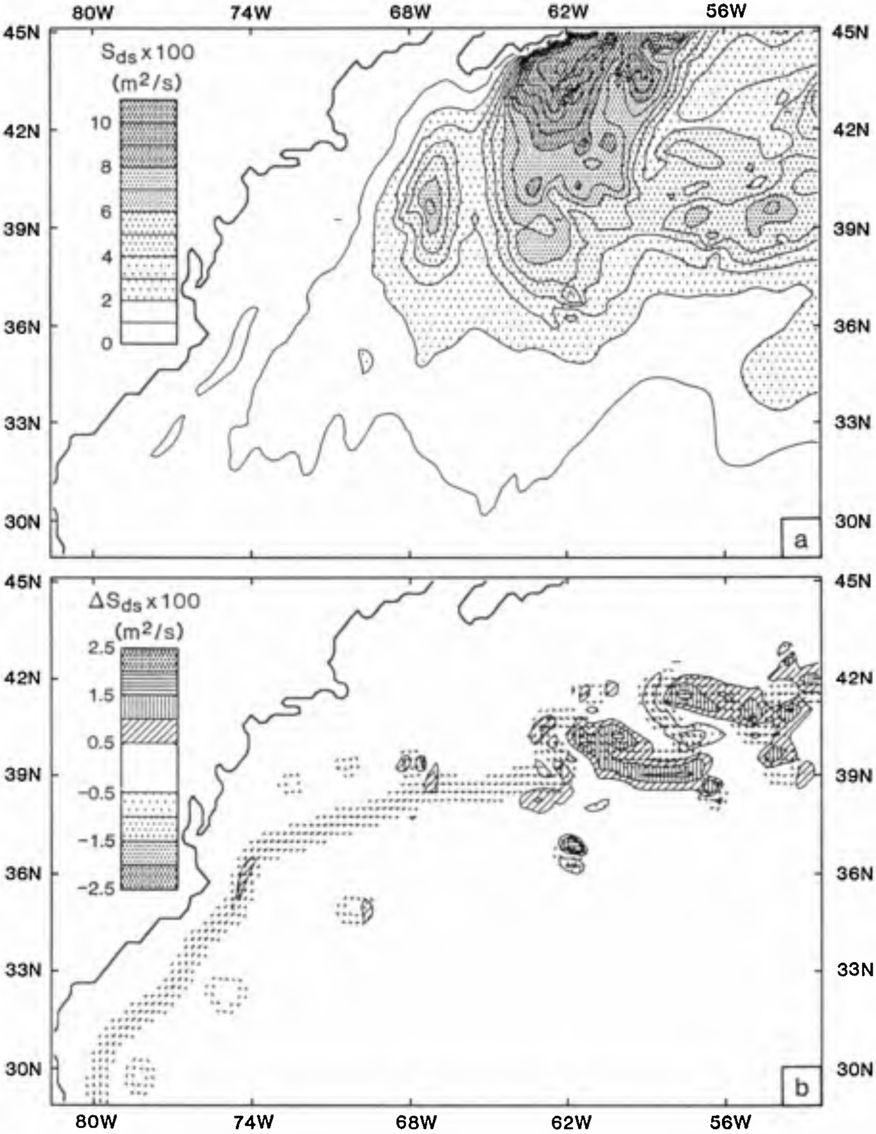

Fig. 6 Like Fig. 3 for integral dissipation (whitecapping) source term $S_{ds,i}$.