Air-Sea Fluxes and Boundary-Layer Structure Over the Japan/East Sea During Winter Cold-Air Outbreaks

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INTRODUCTION

Strong northwesterly wintertime winds resulting from the incursion of dry and cold air masses from the Eurasian continent into the Japan/East Sea (JES) known as "cold-air outbreaks" greatly enhance the air-sea interaction over JES. In particular, an area about 150 km in diameter off Vladivostok (referred to as the "Flux Center" by Kawamura and Wu, 1998, Fig.1) experiences very large fluxes of momentum, sensible and latent heats. We present results of air-sea fluxes and boundary-layer aircraft measurements obtained under such conditions during the Winter 2000 JES experiment.

APPROACH AND METHODS

The NPGS/CIRPAS Twin Otter aircraft (Fig. 2) was instrumented with fast-responding wind, temperature, humidity, IR sea temperature, aircraft motion, and navigation sensors. Thirteen research flights were flown from Misawa NAF, Japan, over the Japan/East Sea. Three basic research goals were addressed with different flight patterns (as shown in Fig. 3):

- Internal Boundary-Layer Growth (IBLG): after transit to the "Flux Center" south of Vladivostok, a line of soundings from 100 to 3000-5000 feet was flown following an approximate streamline across the JES.
- Flux Mapping (FM): after transit to the "Flux Center" south of Vladivostok, the surface-layer fluxes were mapped in a grid pattern at 100 feet with soundings to 5000 feet.
- Flux Divergence (FD): after transit to the "Flux Center" south of Vladivostok, a vertical stack pattern was flown to determine the flux divergence profile in the boundary layer.

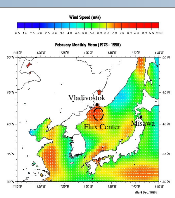

Figure1. February monthly mean wind speed (Na & Seo, 1998).

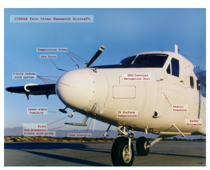

Figure 2. CIRPAS Twin Otter Aircraft with turbulence instrumentation.

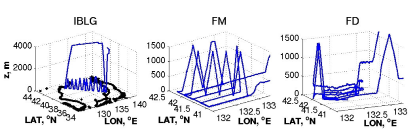

Figure 3. Flight patterns during JES.

RESULTS

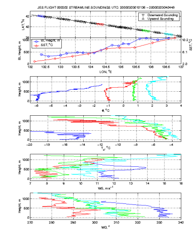

Figure 4. Vertical structure and growth of JES MABL along an approximate streamline on February 03, 2000.

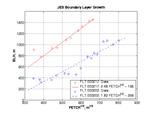

Figure 5 Internal boundary-layer growth with fetch $^{1/2}$ for flights 000202 and 000217 (February 03 and 18, 2000).

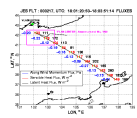

Figure 6. Surface turbulent fluxes for flight 000217.

An example of the boundary-layer growth across the JES is shown in Fig. 4 for Feb 3 2000. The flight track was to the SW, and the boundary-layer height as given by the jump in potential temperature varies from about 300 to 1200 meters. Many of the interesting features of the JES MABL are revealed. Down the streamline we observe internal boundary-layer growth in response to the abrupt change in surface conditions from land to ocean. It is accompanied by warming and moistening of the MABL and decay and backing of the wind. Honshu's orography may play a role in the thickening of the MABL as well as on the wind direction backing. Also, the sharp increase in the IBL around 134°E seems to be a response to the crossing of the SST front. Thus there may be *two* internal boundary layers across the JES in cold-air outbreak conditions: the initial IBL and the second IBL caused by the SST front.

Another IBLG pattern was flown on Feb 18 2000 where the much stronger winds (~ 15 m s^{-1}) seemed to be the cause for the faster observed IBL growth. The IBL growth for both days is shown in Fig. 5. The linear fit of the IBL height to the square root of the fetch is very reasonable especially for the stronger wind day. The growth rate of 1.82 (fetch)$^{1/2}$ for Feb 3 2000 is close to the 1.91 m$^{1/2}$ found near shore by Hsu (1986).

Eddy correlation fluxes for flight 000217 were estimated along the 5-6 minutes deck level runs flown at roughly 40 m between each sounding pair. The results are summarized in Fig. 6 for along-wind momentum, sensible heat and latent heat fluxes. It can be observed that the combined fluxes are the largest inside the "flux center". These direct measurements seem to confirm the findings of Kawamura and Wu (1998) who suggested the presence of the "flux center". Their study relied only on indirect methods: satellite data (NSCAT) and ECMWF predictions. Immediately outside the flux center, the heat fluxes decreased considerably (more than 50% for sensible heat) before they started to increase again past the 40°N which is roughly the location of the SST front. Both latent and sensible heats fluxes increased greatly in the vicinity of Honshu as a result of the relatively warmer water and the island's orography.

Data from low-level (40 m) runs of all JES flights were combined to examine the variations of momentum flux. The momentum flux at 40 m is shown in Fig. 7 as the friction velocity u^*, and the drag coefficient C_D as functions of the wind speed. These variations including the ~ 25 % jump in the drag coefficient above ~16 m s^{-1} are very similar to those reported by Garratt (1977). The increase in breaking waves may be responsible for the jump in C_D but this is only a speculation since we did not have any wave measurement or imaging.

Two days, February 25 (winds ~ 10 m s^{-1}) and February 28 (winds ~ 20 m s^{-1}) were dedicated to measuring flux divergence. The variations of the three measured fluxes with height were obtained from several "stacked" level runs at different heights and are shown in Fig. 8 for the two flights.

RESULTS (Continued)

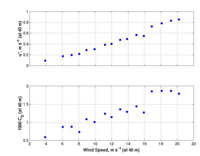

Figure 7 Variations of u^* and C_D over JES with wind speed at 40 m.

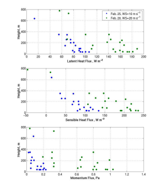

Figure 8 Variations of latent and sensible heats and momentum fluxes with with height.

COMPARISONS WITH COAMPS MODEL

One of the goals of JES is to provide detailed in situ measurements to be used for evaluation and eventually validation of mesoscale numerical models. Because of the large horizontal and vertical coverage of research aircraft, the data obtained by the CIRPAS Twin Otter in JES are particularly suitable for comparison with these models.

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is a three-dimensional non-hydrostatic model developed at the Naval Research Laboratory (NRL). Details of COAMPS can be found in Hodur (1997). The COAMPS simulations were set up to start at 00 UTC on January 30 2000 and continued until February. 4. The model was initialized by the Naval Operational Global Atmospheric Prediction System (NOGAPS) analysis field at the model starting time. The boundary condition also came from NOGAPS analysis field updated every 6 hours. Three grid meshes were used with resolutions of 9 km, 27 km and 81 km from the inner to the outmost nest respectively, and 30 uneven levels in the vertical with about 10 levels within the atmospheric boundary layer. Data assimilation was made at 00 and 12 UTC each day for the outermost domain only to reduce the influence of the observations on the model results for the inner domain while keeping the inner domain boundary conditions as close as possible to the observed large-scale field.

In the simulation, we used a Louis surface flux parameterization (Louis 1979) modified to allow different roughness lengths for momentum and scalars. The Mellor-Yamada (1982) level-2.5 boundary layer scheme was used for boundary layer turbulent mixing. The results from COAMPS in the figures were taken at nearly the same (or as close as possible, COAMPS output files are hourly) as the time and location of the aircraft observation.

Aircraft data – COAMPS comparison results of mean quantities of potential temperature, mixing ratio and wind speed as well as fluxes of latent and sensible heats and momentum are given in Fig. 9. The overall evaluation so far is not very conclusive. For instance, there seem to be a reasonable agreement at the low-end values of sensible heat flux whereas at the high-end COAMPS predictions are significantly larger than the measured values. We do not have an explanation yet for the discrepancies. We are in the process of conducting systematic comparisons encompassing the whole aircraft deployment period. We hope this will help us identify the source of the discrepancies and refine our model further.

COMPARISONS WITH COAMPS MODEL

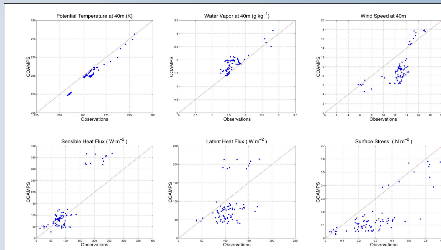

Figure 9 Comparisons of observations to COAMPS predictions of potential temperature, mixing ratio and wind speed (top left to right) and sensible heat flux, latent heat flux and surface stress (bottom left to right).

CONCLUSIONS

- A dramatic growth of the internal boundary layer (IBL) as a response to the cold and dry continental air outbreak into the JES (flights 000202 and 000217) was observed.
- A smaller secondary IBL due to the mid-JES SST front was also observed.
- Turbulence instrumentation performed reasonably well given the extreme meteorological conditions.
- The larger fluxes measured in the "Flux Center" are in agreement with Kawamura and Wu's (1998) study.
- Variations of CD are in agreement with the review of Garratt (1997) particularly the jump at about 16 m s^{-1}.
- Data suggest Honshu's orography may play a significant role in the southern part of the JES.
- We do not have an explanation yet on why COAMPS predictions agree in some instances with the observations and disagree in others (e.g., sensible heat flux).

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