Underestimation of Latent and Sensible Heat Fluxes above the Agulhas Current in NCEP and ECMWF Analyses

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ABSTRACT

The Agulhas Current is the major western boundary current of the Southern Hemisphere. South of Africa it retroflects back into the southwest Indian Ocean, transporting relatively warm water into the midlatitudes. Large sensible and latent heat transfers from the Agulhas Current and its retroflection to the atmosphere occur throughout the year, but particularly during winter. This study suggests that the NCEP and ECMWF models tend to underestimate these fluxes because they are unable to adequately represent the air–sea fluxes over the warmest waters in the core of the current. This core is only 80–100 km wide and it is suggested that the SST data used by these models do not have fine enough spatial resolution to properly represent the Agulhas Current and its mesoscale variability.

1. Introduction

In the Northern Hemisphere, the Gulf Stream and the Kuroshio Currents play an important climatic role by transporting warm subtropical water poleward along the continental margin before turning offshore into the open midlatitude ocean. Large sea surface temperature (SST) gradients exist between these western boundary currents and the ambient North Atlantic and North Pacific waters. In winter, the air–sea temperature difference between these currents and cold, dry air advected by the westerlies off eastern North America and Asia is pronounced and this leads to substantial heat losses from the ocean. A recent climatology (Josey et al. 1999) suggests that winter climatological latent and sensible heat fluxes from the Gulf Stream and Kuroshio Currents to the overlying atmosphere are of the order of 200–300 and 50–100 W m^{-2}, respectively. Summer heat fluxes are smaller (respectively 50–100 and -15 to 15 W m^{-2}) but are still substantial.

In the Southern Hemisphere, the Agulhas Current is by far the strongest western boundary current. It flows along the east coast of South Africa before moving offshore near 34°S and subsequently retroflecting back into the midlatitude southwest Indian Ocean. While the climatological heat fluxes associated with the Agulhas Current are smaller than those for the Gulf Stream or the Kuroshio, there is generally less seasonal variability in its heat losses to the atmosphere. Climatological winter fluxes are about 100–150 W m^{-2} for latent and 15–30 W m^{-2} for sensible heat (Josey et al. 1999). It is likely that the smaller heat fluxes result from the continental landmass of southern Africa terminating in the subtropics (34°–35°S) and it being relatively narrow; hence, the air masses (essentially marine) that are advected by the westerlies over the southern Agulhas Current are typically less cold and dry than those transported over the Gulf Stream and the Kuroshio. Nevertheless, there is evidence that, like its Northern Hemisphere counterparts, heat exchange between the Agulhas Current and the overlying atmosphere does significantly influence the regional climate (e.g., Jury et al. 1993; Crimp et al. 1998; Reason 2001) and may have a significant effect on the intensity of some local storms (Rouault et al. 2002).

Heat losses from these western boundary currents can be much larger during significant weather events such as storms. Ship or buoy measurements of the net turbulent heat fluxes on the order of 1000 W m^{-2} have been made during a storm passage across the Gulf

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Stream, Kuroshio, and southern Agulhas Current (Xue et al. 1995; Kondo 1976; Rouault and Lutjeharms 2000). The large fluxes from these currents and sharp SST gradients near their boundaries may also lead to transitions in marine atmospheric boundary layer stability and they can trigger secondary mesoscale circulations (Rouault et al. 2000; Friehe et al. 1991; Khalsa and Greenhut 1989). Measurements in the Agulhas Current have shown substantial transfers of water vapor in the marine boundary layer, and a deepening of the marine boundary layer due to intense mixing and unstable atmospheric stability created by the advection of colder and drier air above the current (Lee-Thorp et al. 1999; Rouault et al. 2000). The intensity of mixing in the local boundary layer is such that even during anticyclonic subsident conditions, cloud lines can be observed above the current (Lutjeharms et al. 1986; Lee-Thorp et al. 1998; Lutjeharms and Rouault 2000).

Several studies have also investigated the potential influence of surface fluxes off these strong western boundary currents on the evolution of severe storms. For example, Bosart and Lin (1984) have linked the Gulf Stream and the Presidents' Day Storm of 1979 while Rouault et al. (2002) have provided evidence of the influence of the Agulhas Current on the evolution of a severe convective storm over southern South Africa. More generally, Bane (1989) has studied the potential effect of the Gulf Stream on winter storms and cold air outbreaks. Modeling studies (e.g., Holt and Raman 1992) have shown that the Gulf Stream has a role in the development or intensification of winter storms along the U.S. east coast. Several studies have also considered the potential influence of the Gulf Stream and Kuroshio Currents on extratropical cyclone characteristics (e.g., intensity, frequency, and duration) and on cyclogenesis (e.g., Gulev et al. 2001; Holt and Raman 1990; Bosart and Lin 1984). More recently, Reason and Murray (2001) and Reason (2001) have, respectively, shown the sensitivity of extratropical cyclone characteristics in the south Indian and South Atlantic Oceans to decadal SST variability in the Agulhas Current region and to the presence of the Agulhas Current itself.

Given all this evidence of the significance of air–sea heat fluxes in the Agulhas Current region to the regional atmospheric circulation, the objective of this note is to consider the ability of operational models from the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) to adequately represent this important heat transfer. We present evidence below that, contrary to what has previously been found for the Gulf Stream and Kuroshio (Moore and Renfrew 2002; Renfrew et al. 2002) the fluxes for the Agulhas Current are substantially underestimated by these models. One obvious shortcoming of the models may be their inadequate spatial representation of the warm core of the Agulhas Current, and we therefore consider the potential discrepancies between the SST used by the reanalyses and those measured in situ or by higher-resolution satellite data from the Tropical Rainfall Measuring Mission (TRMM) and the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) satellites.

2. Comparison between ECMWF operational and NCEP four daily reanalysis and in situ estimates

Before comparing in situ fluxes estimated during the Agulhas Current Air–Sea Exchange Experiment (ACASEX; Rouault et al. 1995) of austral autumn 1995 with the NCEP and ECMWF values for the same period, it is useful to give some details on the ECMWF operational and NCEP reanalysis data.

The ECMWF products have been taken from the ECMWF operational archive, which are short-range forecasts for the time range from 12 to 36 h. Data are available from the ECMWF Web site at http://www.ecmwf.int. The idea behind using these forecasts is to be sufficiently close to the analysis time to have an accurate representation of the atmospheric fields but to avoid the rapid model adjustment to the data just after this time. The 12–36-h time range is a reasonable compromise, because most of the spinup in precipitation and evaporation occurs during the first 12 h. The 1995–96 ECMWF data used here have a spectral resolution of triangular wavenumber 213 (T213), which corresponds to a grid spacing in physical space of about 60 km. However, the effective resolution is on the order of 100 km since half a wavelength is about 100 km in a T213 spectral resolution. For the NCEP reanalyses used here, the resolution is lower (triangular wavenumber T62) or about 210-km grid spacing (see data online at http://sgi62.wwb.noaa.gov:8080). Both models use the sea surface temperature analyzed daily by NCEP and provided on a $1° \times 1°$ regular grid. This SST field is then interpolated to the model grids consistent with their land–sea mask. SST is kept constant during the ECMWF forecast.

Surface flux computations are part of the ECMWF turbulence scheme, which is described by Beljaars and Viterbo (1998). The algorithm for air–sea interaction is based on Monin–Obukhov similarity extended with a gustiness formulation for low wind speed (Beljaars 1995). The roughness length for momentum has a Charnock term (with a Charnock parameter of 0.018) and smooth surface term (scaling with friction velocity and kinematic viscosity). The roughness lengths for heat and moisture have a smooth surface term only. In the NCEP reanalyses, the flux algorithm is detailed in Zeng et al. (1998) and is a simplification of the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) algorithm described in Fairall et al. (1996).

Fluxes from these models over the Agulhas Current are compared below with those obtained in situ from

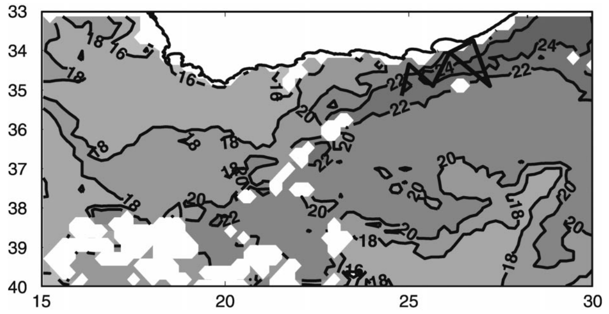

FIG. 1. The 18-km resolution AVHRR Pathfinder 8-days-mean SST averaged over the period 23–30 Apr 1995 during which the ACASEX cruise took place. The ACASEX ship track is shown in black. The core of the Agulhas Current has SST > 22°C. White areas over the ocean correspond to missing data due to persistent cloud or problems in the AVHRR Pathfinder SST algorithm.

various cruises, principally the ACASEX cruise. ACASEX was the first cruise dedicated to an air–sea interaction experiment in the Agulhas Current and its major aim was to study the influence of the Agulhas Current on the marine atmospheric boundary layer. Figure 1 shows the SST measured during the ACASEX cruise of 23–30 April 1995 with the associated ship track across the current outlined in black. This portrayal gives an 8-day mean with a 18 km × 18 km spatial resolution based on AVHRR observations. The AVHRR 9 km × 9 km resolution SST looks very similar to the one given in Fig. 1. The triangular part of the cruise track was covered about 10 times during this period. Missing SST data in Fig. 1 correspond to areas that experienced persistent cloud cover during the 8-day period (16 overpasses). Clearly evident in Fig. 1 are the roughly 100-km-wide core of the current as well as the relatively sharp SST gradients inshore of the Current and also in the region of the Agulhas Return Current along about 39°–41°S.

During ACASEX, a thorough investigation was made of the turbulent heat exchange between the ocean and atmosphere, the net heat budget of the ocean, and the structure of the marine atmospheric boundary layer. A full and detailed description of the instruments used, their calibration, and the experimental methodologies employed can be found in the relevant publications (e.g., Rouault and Lee-Thorp 1997; Rouault et al. 1997, 1999) but, in essence, the bulk method algorithm developed by Fairall et al. (1996) for TOGA COARE was used. Using TOGA COARE and the Tropical Atmosphere Ocean (TAO) data, Zeng et al. (1998) have performed an intercomparison of bulk aerodynamic algorithms for computing sea surface fluxes (ECMWF, NCEP, in situ) and the reader is referred to this study for further details on these flux algorithms. During ACASEX, the turbulent fluxes were estimated with transfer coefficients that relate the fluxes to 10-m mean values of routinely measured variables. The fluxes are determined in an iterative process as a function of the atmospheric stability parameter. This parameter is equivalent to the Richardson number, which is the ratio of the work done by or against the buoyant turbulent forces and the rate of shear production of turbulent energy, and determines whether surface atmospheric conditions are stable, neutral, or unstable. We account for the difference in temperature between the ship inlet (a few meters from the sea surface) and the real SST and for diurnal variations in skin temperature. The resulting value is the calculated SST that we use in our comparison below.

The ACASEX measurements (Lee-Thorp et al. 1999; Rouault et al. 2000) show that the core of the Agulhas Current (SST > 22°–23°C), about 80–100 km wide, transfers about 5 times as much water vapor to the atmosphere as does the surrounding water. These results give credence to the assertion by many investigators (e.g., Walker 1990; Mason 1995; Reason and Mulenga 1999) that moisture uptake above the Agulhas Current may contribute significantly to moisture convergence and rainfall over the interior of South Africa.

The relatively cold coastal water between the coast and the Agulhas Current, which occurs via current-induced upwelling (Lutjeharms et al. 2000), is shown as missing data in Fig. 1. However, typical coastal temperatures at this time of year are 13°–16°C, creating a strong SST gradient between them and those of the Agulhas Current. The spatial portrayal of the warm surface water of the Agulhas Current in this figure is therefore relatively coarse. The missing coastal data in Fig. 1 may be due to the algorithm used here (version 4.2) since these areas are often cloud free, or at least less cloudy than the Agulhas Current itself (Lutjeharms and Rouault 2000; Rouault et al. 2002). However, assessment of the earlier algorithm version (4.1) by Vazquez-Cuervo and Sumagaysay (2001) suggests that the maximum difference over the world's oceans between AVHRR-derived SST and in situ data for the 1992–96 period was 0.24°C in the Caribbean—in the Indian and South Atlantic region of interest here it was about 0.1°C. This suggests that it is more likely to be the model representation of this SST field that leads to the flux discrepancies. Here, the focus is on these flux discrepancies over the core of the current on the ACASEX cruise track that were not significantly affected by missing AVHRR SST data (Fig. 1).

Figure 2a shows a comparison between the ECMWF and in situ fluxes estimated above the core of the Agulhas Current (SST > 23°C) during the 24 April–1 May 1995 period. This represents 445 points or 90 h of measurement during various meteorological conditions. It is clear that ECMWF significantly underestimates the latent heat fluxes (and also sensible heat fluxes—not shown) during this period. The mean latent heat flux estimated by the ship instrumentation during ACASEX was 210 W m^{-2} while that for ECMWF was 167 W m^{-2}. For sensible heat, the mean flux obtained from the ship measurements during ACASEX was 42 W m^{-2} while the ECMWF value for this period was only 27

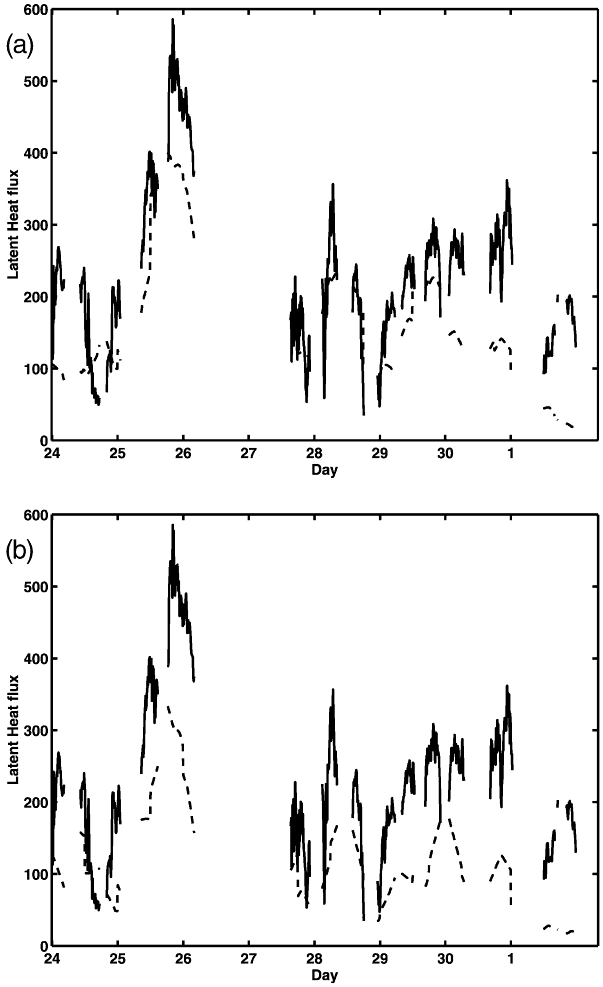

FIG. 2. Comparison between latent heat fluxes estimated during the ACASEX cruise (thick line) and the 4 times daily (a) ECMWF operational forecast values and (b) NCEP reanalysis values (dashed line). NCEP and ECMWF values are interpolated from the grid to the location of the measurements. Comparison is for measurements taken in the core region of the Agulhas Current only (SST $>$ 22°C).

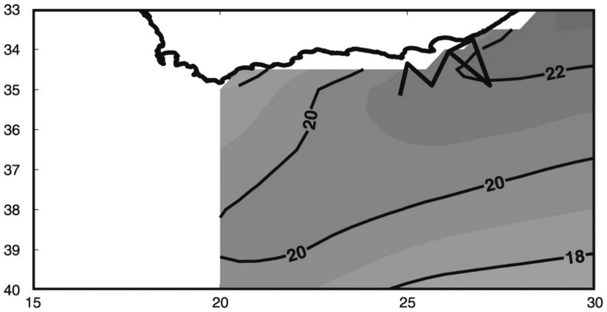

FIG. 3. ECMWF 4 times daily SST averaged over the ACASEX cruise period. The cruise track of the ACASEX is shown in black. No data is displayed west of 20°E or above land.

W m^{-2}. Similar large discrepancies exist between the NCEP and in situ fluxes as well (e.g., Fig. 2b—mean NCEP latent heat flux was 119 W m^{-2}).

Figure 3, which is the Agulhas Current SST used by ECMWF, indicates the likely source of the flux discrepancies. The narrow core of the current is not well represented and the SST gradients are considerably less well defined than those in Fig. 1. There is also little evidence of any eddy, meander, or filament SST structure in Fig. 3 unlike what is typically observed. The mean AVHRR SST for the core of the Agulhas Current was 23.5° with a maximum of 24.5°C. By comparison, the corresponding interpolated mean ECMWF SST for the current core was 1.5°–2° lower (21.9°C). While the optimal interpolation (OI) SST (Fig. 4) used by NCEP is slightly higher than the ECMWF SST (Fig. 3), it still does not adequately represent either the core of the Agulhas Current or the mesoscale SST gradients of the region. Note that the differences between the ECMWF and NCEP SST (Figs. 3–4) likely result from interpolations to the respective model grids since both used the same 1° resolution daily SST forcing.

Further evidence supporting the suggestion that SST underestimation is the main cause for the discrepancies between the in situ and model latent and sensible heat fluxes comes from comparing fluxes calculated using the Fairall et al. (1996) bulk algorithm. Using the mean meteorological parameters measured in situ for the core of the Agulhas Current (wind speed = 8.6 m s^{-1}, SST = 23.5°C; air specific humidity at 10 m = 10 g kg^{-1}; air temperature at 10 m = 18.2°C; saturated specific humidity at the sea surface = 18 g kg^{-1}; and air pressure = 1020 hPa), a latent heat flux of 240 W m^{-2} and a sensible heat flux of 65 W m^{-2} are obtained. Reducing the SST by 2°–21.5°C and the corresponding saturated specific humidity at the sea surface to 15.8 g kg^{-1}, results in a latent heat flux of 172 W m^{-2} and a sensible heat flux of 37 W m^{-2}, values that are much closer to the ECMWF operational model values of 167 and 27 W m^{-2}, respectively.

To demonstrate similar flux discrepancies in other parts of the Agulhas Current, we present measurements that used the identical ACASEX flux instrument package. They were obtained aboard the research vessel *Algoa* during the recovery cruise of the Agulhas Current

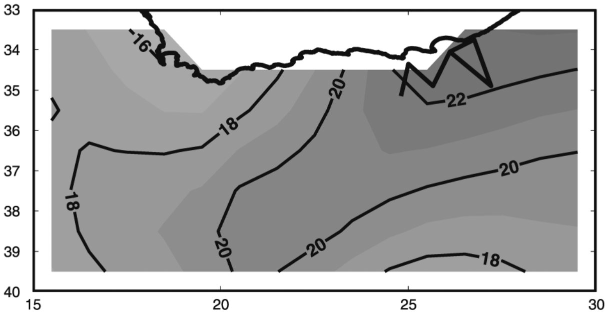

FIG. 4. The OI (1° × 1° resolution) SST (Reynolds and Smith 1994) used by NCEP for the ACASEX cruise period.

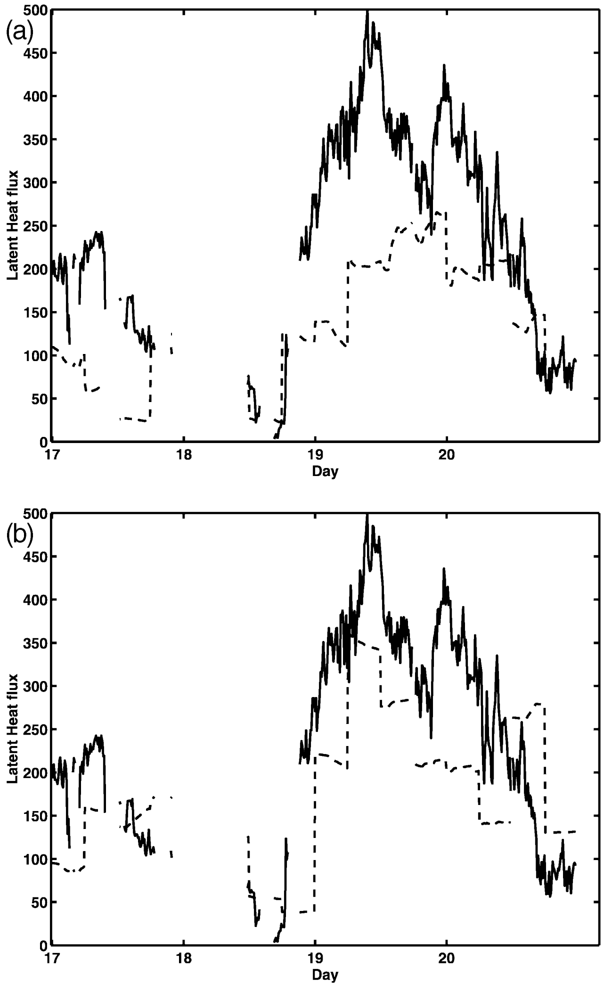

FIG. 5. Same as in Fig. 2 except that this comparison is for the ACE recovery cruise of 17–21 Apr 1996 that took place in the northern Agulhas Current (near 31°S). Comparison is for SST greater than 23°C when the ship was above the core of the current.

Experiment (ACE; Bryden 1995) during 17–21 April 1996. The track in this case was in the northern Agulhas Current near 31°S and a total of 72 h of measurements were made. The results are similar to the preceding discussion for the ACASEX cruise. Ship-estimated SST had a mean value of 24.7°C as compared to ECMWF value of 22.5°C. Averaged over the cruise, the in situ latent heat flux estimate was 264 W m^{-2} as compared to the ECMWF value of 171 W m^{-2} and the NCEP value of 185 W m^{-2} (Fig. 5). For sensible heat fluxes, the in situ estimate was 47 W m^{-2} whereas the corresponding ECMWF value was only 32 W m^{-2}.

The fluxes calculated with the Fairall et al. (1996) bulk algorithm using meteorological parameters averaged above the Agulhas Current (wind speed = 9.3 m s^{-1}, SST = 24.7°C; air specific humidity at 10 m = 11.5 g kg^{-1}; air temperature at 10 m = 21.3°C; saturated specific humidity at the sea surface = 19 g kg^{-1}; and air pressure = 1016 hPa) are 239 W m^{-2} for the latent and 41 W m^{-2} for the sensible heat flux. Reducing the SST by 2°C and the corresponding saturated specific humidity at the sea surface to 16.8 g kg^{-1} leads to a latent heat flux of 164 W m^{-2}, again closer to the ECMWF operational and NCEP reanalysis values.

Other cruise data (not shown here) at different times of the year (e.g., the ACE cruise in February 1995; Bryden 1995) or previous cruises to Marion Island (Rouault and Lee-Thorp 1997) that cross the Agulhas Current and during which flux measurements have been made lead to the same conclusion—the underestimation of the latent and sensible heat fluxes by the models most likely results from the SST being too cool, either because of the coarse resolution of the models or the SST products used. The results from these other cruises further support the claim that operational models and their reanalyses tend to underestimate the latent and sensible heat fluxes over the Agulhas Current.

3. Discussion and conclusions

Analyses by Renfrew et al. (2002) for a high heat flux event over the Labrador Sea region indicate that the NCEP fluxes overestimated the in situ fluxes there. These authors attributed this overestimate to the NCEP surface layer formulation calculating roughness lengths for heat and moisture that are too large during high winds. Other comparisons in open-ocean areas also suggest an overestimation of the latent and sensible heat fluxes by NCEP and ECMWF models (Weller et al. 1998; Josey 2001). Moore and Renfrew (2002) have shown a similar NCEP overestimate of heat fluxes during a cold air outbreak over the Gulf Stream, compared to the observations of Xue et al. (1995). However, when the fluxes were recalculated using the Smith–deCosmo algorithm (Smith 1988; deCosmo et al. 1996), better agreement was achieved. Typical SST differences between NCEP and buoys along the eastern seaboard of North America are of the order of only a few tenths of a degree as compared to about 2° noted above for the Agulhas Current core.

Contrary to experience for the Gulf Stream and Kuroshio (Renfrew et al. 2002; Moore and Renfrew 2002), the data presented here suggest that both the NCEP and the ECMWF reanalyses significantly underestimated the in situ latent and sensible heat fluxes for the Agulhas Current during the ACASEX and ACE cruises and may well do so in general. Although application of the Smith–deCosmo algorithm could improve matters, we believe that this consistent underestimate mainly results from the models being unable to adequately represent the 80–100-km-wide core of the Agulhas Current or the sharp SST gradients associated with it. Because the core of the Agulhas Current is often covered with clouds (Lutjeharms and Rouault 2000; Lee-Thorp et al. 1998), SST estimated by the Tropical Rainfall Measuring Mission (TRMM) is likely to be more accurate than that derived from AVHRR data. The TRMM Microwave Imager (TMI) can measure SST at a resolution of 25 km through clouds and the TRMM satellite orbits the earth between 15 and 16 times daily with the Agulhas Current region in the field of view of the TMI instrument from 2 to 4 times a day. This is a great advantage over the infrared SST observations that require a cloud-free field of view. Taking account of TRMM-derived SST estimates in flux calculations for cloudy ocean areas is likely to help reduce discrepancies between model and in situ values.

We note that NCEP has been using a 0.5° resolution SST product since May 2001, improving SST gradients in the Gulf Stream and Kuroshio regions for example (Thiebaux et al. 2001)—however, the model is not run at this resolution. The ECMWF resolution has now been increased to T511 or about 40 km in gridpoint space (during the 1995–96 period of interest here it was T213 or roughly 60 km in gridpoint space) with the lowest vertical level moved down from 30 to 10 m and the 0.5° SST data are also being used. ECMWF have also been using a fully coupled wave model (Janssen and Viterbo 1996) since June 1998, which provides a sea state–dependent Charnock parameter to the air–sea flux algorithm every hour—this may well improve matters in the Agulhas region given the frequency of rough sea state in this location. While such model improvements could mean that the differences between ECMWF and NCEP fluxes for 2001 and later and those estimated in situ could be less than reported here for 1995–96, it is likely that to resolve the fluxes over the Agulhas Current in a large-scale data assimilation system, an SST analysis at 25-km resolution or better and a model that is capable of maintaining this horizontal resolution in the boundary layer is needed. This relatively high resolution is needed due to the tight gradients in SST between the Agulhas Current core and ambient waters and the associated fluxes (e.g., the ACASEX cruise showed that the latent heat flux over the core was about 5 times greater than that over the ambient waters—Lee-Thorp et al. 1999; Rouault et al. 2000). Such an increase in resolution is considerable and introduces other considerations such as computational resources. It may well be that a preferable approach is to nest a limited-area model over sensitive heat flux regions like the Agulhas Current.

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