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Influence of upwelling, subsurface stratification, and heat fluxes on coastal sea surface temperature off southwestern New Caledonia

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[1] Strong cooling events off the western barrier reef of New Caledonia have been recently observed and attributed to wind-driven coastal upwelling. A simple one-dimensional model based on a heat budget in the mixed layer is developed and calibrated to explain the daily variations of sea surface temperature (SST) observed at a coastal station off southwestern New Caledonia from 1992 to 2005. This model takes into account the daily wind-forced vertical advection and air-sea heat fluxes, as well as seasonal variations of the subsurface temperature stratification. It can explain a large part of the daily SST variations and helps to quantify the relative contribution of the main vertical processes involved in these variations. The model shows that upwelling is the dominant process at daily timescale, and its SST signature is strongly modulated by the seasonal variations of the subsurface stratification. The surface heat fluxes have a smaller influence than upwelling on daily SST variations. Coastal chlorophyll *a* concentration increases during upwelling events.

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1. Introduction

[2] Although not located in an oceanic eastern boundary system, New Caledonia presents a favorable configuration for upwelling along its western coast (Figure 1). This 400-km-long island, located in the southwest Pacific, is surrounded by a shallow lagoon and a coral barrier reef, with a very steep external slope. The island and its reef are elongated in the SE–NW direction. In this tropical region, the atmospheric regime is mainly characterized by southeast trade winds, which blow almost parallel to the axis of the island. Trade winds represent about 70% of the total wind occurrence while westerly wind events, associated with low-pressure systems including cyclones, represent less than 15% of the occurrence [Météo-France, 1995]. Upwelling, by supplying nutrients to the euphotic zone, may have important biological implications for the oligotrophic waters off New Caledonia, and particularly for coastal fisheries.

[3] Recently, *Hénin and Cresswell* [2005] showed that coastal sea surface temperature (SST) cooling events along the western barrier reef of New Caledonia, visible on

satellite images, are usually associated with strong trade wind events, which they related to upwelling. According to their descriptive study, these cooling events take up to 5 days to develop, and their spatial extent is around 10–50 km across shore and several hundred kilometers along-shore. They also noted that cooling events mostly occur in summer.

[4] The aim of this paper is to go beyond the descriptive phase and to explicitly link the driving term of upwelling, the wind, to SST, through a simple physical model applied to New Caledonia. The model is based on a one-dimensional heat budget in the mixed layer. It takes into account the daily wind-forced vertical advection and air-sea heat fluxes, as well as seasonal variations of the subsurface temperature stratification. It is calibrated with a 12-year time series of observed coastal SST. With this model, we intend to show the observed cooling events are due to wind-driven upwelling. The characteristic temporal and spatial scales of upwelling can be deduced from its calibration, and compared to those deduced from the descriptive analysis. Moreover, the model allows us to test the relative sensitivity of SST to the upwelling process, subsurface stratification and surface fluxes. It is used as a tool to explain the observed seasonality of cooling events.

[5] Data available in the region are presented in section 2. In section 3, spatial features and temporal variability of coastal upwelling off New Caledonia are described on the basis of combined remote sensing data and in situ measurements. In section 4, the main processes of the coastal upwelling are investigated: its SST signature is statistically analyzed, then the simple SST model is introduced and

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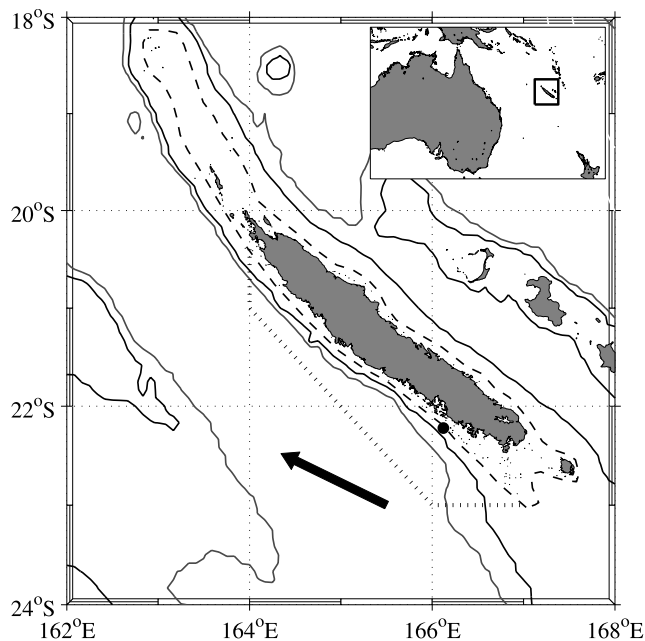


Figure 1. New Caledonia and its location in the South Pacific. Dashed contour around the island represents the barrier reef. Contours of 1500 and 2500 m isobaths are also displayed. All the XBT and CTD data available inside the dotted box were used to create monthly long-term means of the temperature stratification, representative of the western coast. Solid black circle shows the location of the Uitoe coastal station. The arrow represents the mean wind direction.

calibrated to the region of study. In section 5, main limitations of the model and results deduced from its application to New Caledonia, as well as the wider implications of upwelling here, are discussed.

2. Data

[6] In situ data used in this paper were collected by the Research Institute for Development (IRD) in Nouméa, New Caledonia. Half-hourly temperature and salinity time series were obtained from a SBE16 thermosalinograph (TSG) deployed at 10-m depth, just outside the barrier reef (Figure 1). These measurements are considered as the reference point for coastal conditions at the surface and in the mixed layer. The measurement accuracies at this coastal station were respectively 0.001°C for temperature and 0.02 for salinity. The record extended from 1992 to 2004. The diurnal cycle was removed, using daily averages. The power spectrum of the temperature time series did not show any diurnal or semidiurnal harmonic signal.

[7] About 130 temperature profiles from expandable bathythermograph (XBT) and conductivity-temperature-depth (CTD) sensors, collected off the western barrier reef (dashed box in Figure 1) over the last 25 years, were used to estimate the vertical temperature gradient ($\partial T/\partial z$) and the mixed layer depth (MLD). The difference between the sea surface temperature (SST) and the temperature at 50-m depth was taken as $\partial T/\partial z$. The MLD was defined as the depth where temperature is 0.5°C lower than SST. The sparse density of profiles only allowed us to build long-term

monthly products. Climatological profiles for February and August, which correspond to the MLD seasonal extrema, are presented in Figure 2. These two months benefit from the best observational coverage (more than 20 profiles). On average, the mixed layer transition is smoother than for individual profiles.

[8] Daily atmospheric data (surface wind stress, latent heat flux and solar radiation flux) were extracted at 22°S , 165°E (the closest grid point to our coastal station) from the National Climate Environmental Prediction (NCEP) reanalysis data set for the 1992–2004 period [Kistler *et al.*, 2001]. These continuous time series are representative of the open-ocean conditions.

[9] Daily 1-km-resolution SST data from the NOAA advanced very high resolution radiometers (AVHRR) were obtained from the IRD reception antenna based in Nouméa. They were processed through a cloud detection algorithm. This ground station acquisition is part of the IRD “Survey of Environment Assisted by Satellite” project [Petit and Ramos, 2002]. Instantaneous 1-km-resolution chlorophyll *a* concentration data from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) were received and processed at CSIRO in Hobart.

3. Description of Coastal Upwelling off New Caledonia

[10] Figure 3 depicts the upwelling conditions during November and December 2004. In situ measurements show the temporal evolution while SST images show the spatial characteristics. During this period, there were three wind events, each one driving a cooling of SST which peaks a few days later. The spatial scale of the first and second cooling events can be seen on the SST image on 20 and 30 November. A band of upwelled water about 10-km wide appears outside the southwestern barrier reef, with temperature close to 22°C , surrounded by 3° – 4°C warmer waters. The coastal cooling also extends to 50 km in coastal plumes. The large cold area observed offshore (23°S , 166°E) on 30 November is probably due to mesoscale processes and

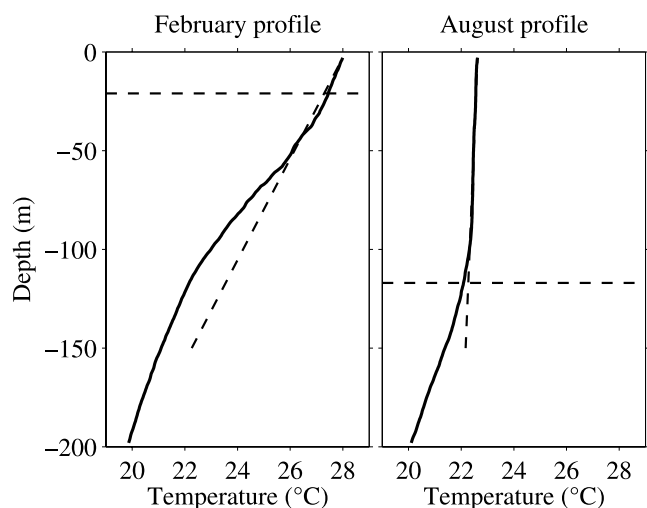


Figure 2. Long-term mean temperature profiles for opposite seasons. The horizontal/vertical dashed line shows the estimated mixed layer depth/vertical thermal gradient.

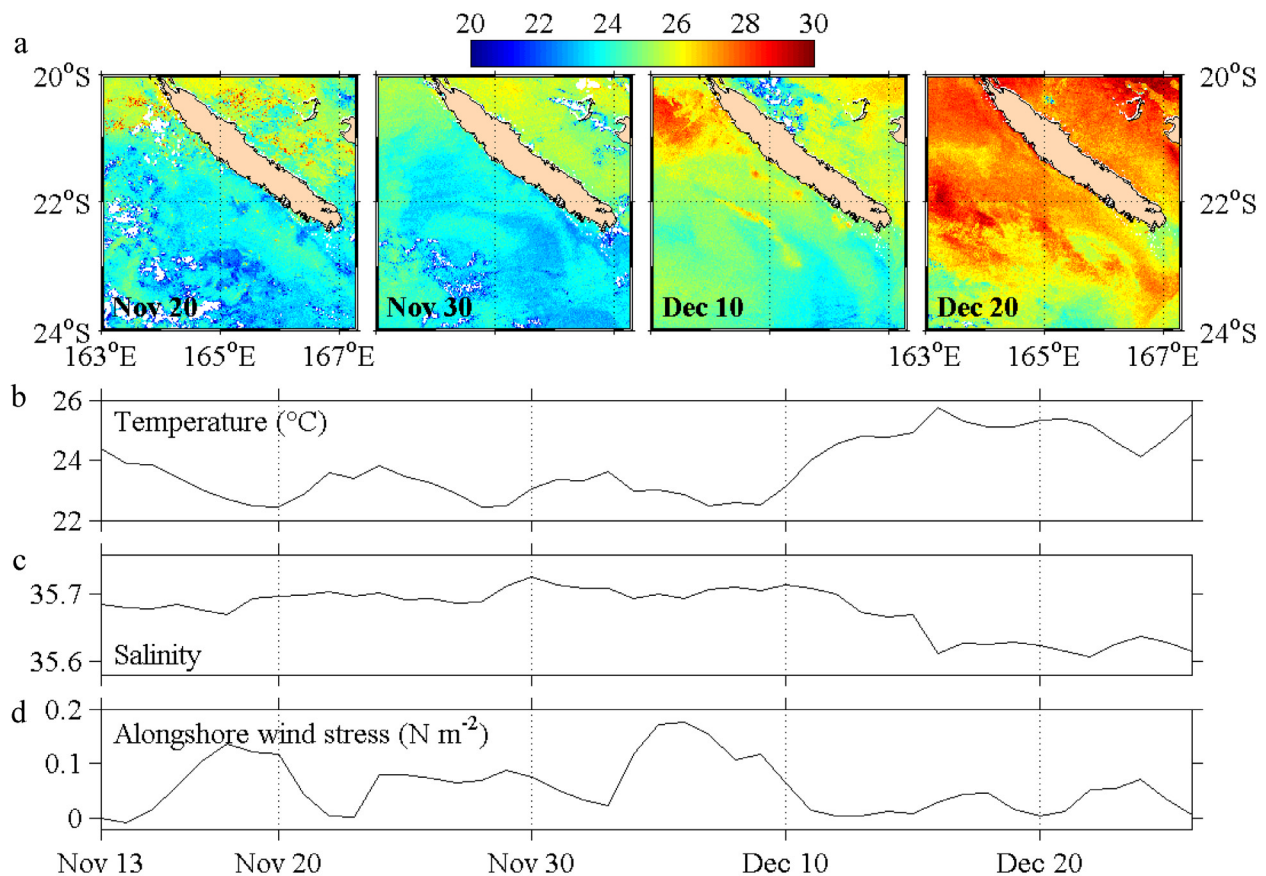


Figure 3. Evolution of the upwelling conditions around New Caledonia over a 40-day period in November–December 2004. (a) Snapshots of AVHRR SST at 10-day intervals, (b) SST and (c) SSS at the coastal station (location in Figure 1), and (d) NCEP alongshore wind stress (positive values denote wind blowing to the northwest).

unrelated to upwelling. On 20 December there was no upwelling at all and tropical warm water spread over the entire region. SST time series from the coastal station reflect the coastal cold/warm conditions observed in satellite images. Higher sea surface salinity (SSS) is characteristic of upwelling events, as there is a subsurface salinity maximum at 160-m depth around New Caledonia, characteristic of the South Pacific Tropical Water [Delcroix and Lenormand, 1997].

[11] Chlorophyll *a* and SST images are compared for two contrasting periods in Figure 4. The apparent high chlorophyll *a* concentrations between the island and the barrier reef (compare Figure 4 and Figure 1) are an artifact of the processing which does not take into account that sunlight is reflected by the shallow waters of the lagoon and the reef itself. In the absence of coastal upwelling (Figure 4c), chlorophyll *a* concentrations are very low immediately offshore the barrier reef toward the open ocean, while during coastal upwelling (Figure 4d) chlorophyll *a* concentrations are increased to between 0.1 and 0.4 mg m⁻³ in a 10-km-wide band along the barrier reef and in plumes reaching 50 km offshore, matching the spatial features of SST cooling. Note that there is no chlorophyll *a* enrichment associated with offshore cooling. The spatial extension of upwelled waters is quite similar to the extension of upwelling centers observed in eastern boundary currents [e.g.,

Rutllant *et al.*, 2004]. In situ measurements on 10 December confirmed the coastal enrichment in chlorophyll, as a response to high coastal nitrate and phosphate concentrations, and also showed enhanced zooplankton concentrations confined to the most southern part of the western reef (A. Vega *et al.*, manuscript in preparation, 2006).

[12] Figure 5 shows the whole 12-year time series used in this study. The wind stress is characterized by high-frequency variations with no clear seasonal signal. The high-frequency SST variations, presumably related to upwelling, are larger during the warm season and superimpose over a clear seasonal cycle. The large SST drops observed in March 1994, March 1996, April 2000, and April 2001 are about the same amplitude as the seasonal cycle (roughly 5°C). They match the strongest peaks in trade wind and correspond to periods of intense upwelling activity, some of which have been described in details by Hénin and Cresswell [2005].

[13] The depth from which waters are upwelled will affect the physical and biochemical consequences of upwelling. This depth, estimated from the peak SST coolings (Figure 5b) and the seasonal climatology of temperature profiles (whose extrema are shown in Figure 2), ranges 100–150 m for the upwelling periods discussed above.

[14] Interannual variations around New Caledonia are linked to large-scale climate variability, dominated by the

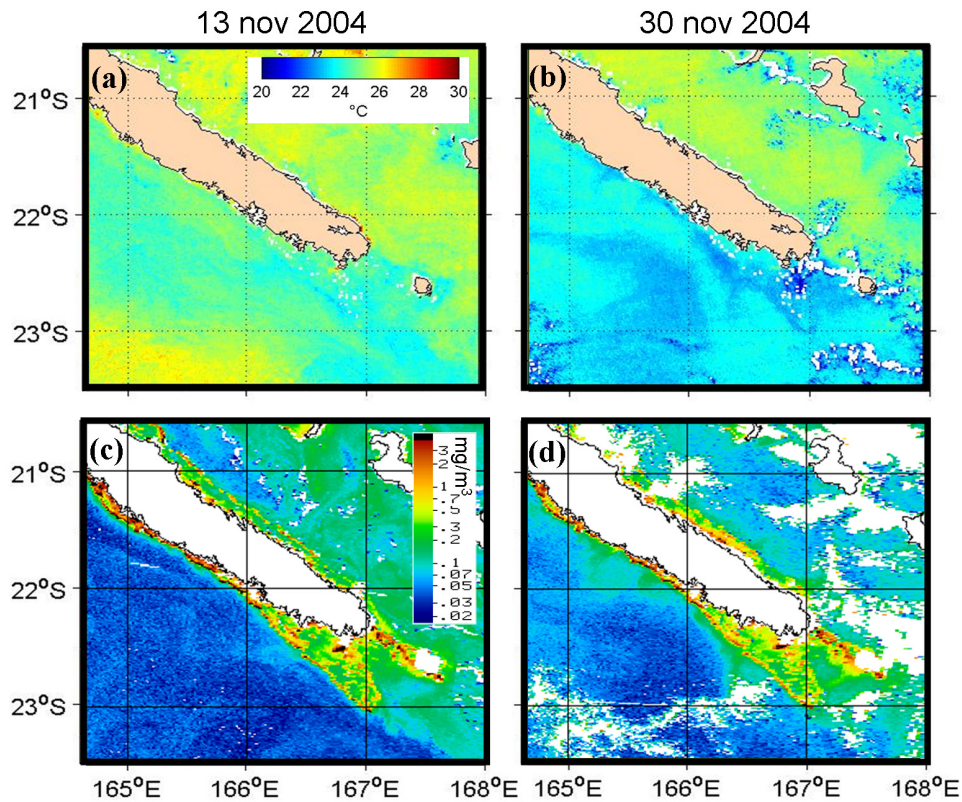


Figure 4. Snapshots of (top) AVHRR SST and (bottom) SeaWiFS chlorophyll *a* on (left) 13 November and (right) 30 November 2004.

El Niño Southern Oscillation (ENSO). In particular, there is usually a slight decrease in SST and a clockwise rotation in the wind direction during El Niño events, while the opposite takes place during La Niña [Delcroix and Lenormand, 1997]. This may be seen in the wind and SST time series (Figure 5) for the very strong El Niño event and subsequent La Niña in 1997–1998. The longest period with weak upwelling favorable wind stress occurred around the December 1997 El Niño peak. When moderate trade winds returned (January 1998), an abnormally strong upwelling

occurred, which is probably due to a thin mixed layer after this no-mixing period. The following winter 1998 was characterized by an anomalously warm SST as a consequence of the La Niña situation.

4. Main Processes Affecting the Coastal SST off New Caledonia

4.1. Upwelling Signature in SST

[15] Daily variations of SST and alongshore wind stress are only moderately correlated over the 12-year time series

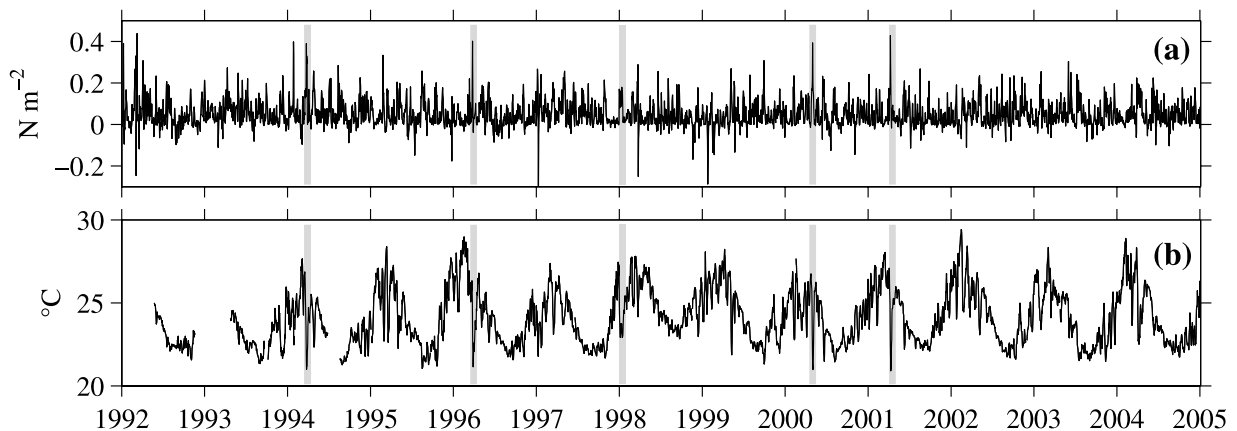


Figure 5. Daily time series of (a) NCEP alongshore wind stress at 22°S, 165°E and (b) SST at the coastal station over the 1992–2004 period. The months of March 1994, March 1996, January 1998, April 2000, and April 2001 are highlighted in grey.

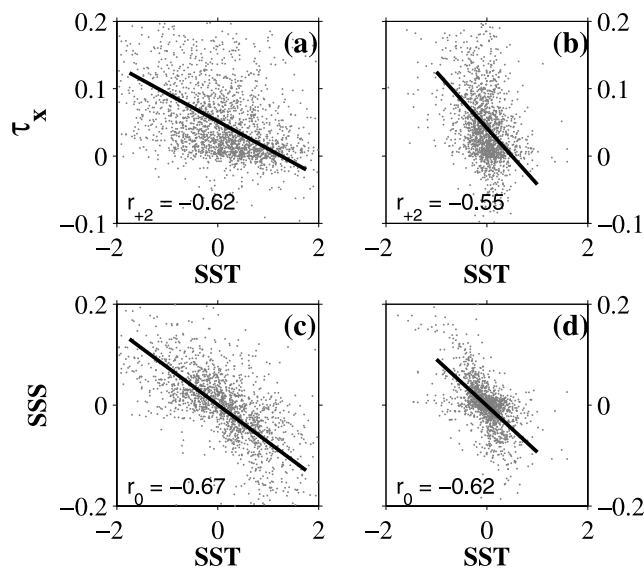


Figure 6. Linear regression (1992–2004) between daily alongshore wind stress and SST anomalies (shifted backward by 2 days) for the period (a) November to May and (b) June to October and between daily SST anomalies and SSS anomalies for the period (c) November to May and (d) June to October. Anomalies are related to a 31-day running mean. The maximum correlation coefficient and corresponding lag (subscript) are displayed in the bottom-left corner of each graph.

($r = -0.46$). The correlation is improved by removing a monthly running mean and introducing a lag on SST (Figures 6a and 6b). This suggests that upwelling is an important process at daily timescale, while other processes affect SST at monthly and longer timescales. The 2-day lag, which corresponds to the maximum cross-correlation, shows that SST responds to the wind conditions over the past few days. The difference in the slope of the regression between the winter and summer seasons denotes a stronger SST response to wind stress in summer, which may be due to seasonal changes in the upwelled subsurface waters. Daily SST and SSS anomalies are negatively correlated (Figures 6c and 6d), as upwelling replace surface waters with colder, saltier waters from the subsurface.

[16] The seasonal variations in the upwelling SST signature, measured by the monthly standard deviation of SST, are compared to seasonal variations in alongshore wind stress and mixed layer depth in Figure 7. At this timescale, changes in the upwelling SST signature cannot be explained by the alongshore wind stress ($r = 0.41$). They seem to be more related to changes in the mixed layer depth ($r = -0.82$). Indeed, a thin mixed layer means cold waters are not very deep; thus it is relatively easy for upwelling to bring them to the surface and cool SST. This provides an explanation for the occurrence of strong cooling events in summer. This analysis suggests an important distinction: upwelling acts at the daily timescale but its SST signature is modulated at seasonal timescale by the subsurface conditions.

4.2. Simple SST Model

[17] To complete the previous statistical analysis, a simple physical model was built to explicitly link wind and

SST. It is based on a one-dimensional heat budget in the mixed layer, taking into account the vertical transport due to wind-forced upwelling, the temperature stratification, and the main air-sea heat fluxes:

$$\frac{\partial T}{\partial t} = \frac{\partial T}{\partial z} \frac{\partial z}{\partial t} + \frac{F}{\rho C_p H} \tag{1}$$

where T is the temperature in the mixed layer of depth H , assumed equal to SST, and taken relative to its seasonal harmonic, F is the heat flux at the surface, ρ is the seawater density and C_p its heat capacity, t is the time axis and z is the vertical axis, oriented upward.

[18] By construction, horizontal advection is neglected in the model. As the coastal station is located just outside the reef, where SST is first affected by the upward transport along the external reef slope, the offshore Ekman advection associated with upwelling probably does not affect the SST variations at the station but propagate them further toward the upwelling front [Brink, 1983]. Alongshore advection by the mean coastal currents seems to interact with upwelling mostly in the northern half of the western reef [Hénin and Cresswell, 2005].

[19] In the coastal upwelling case, the vertical speed is generated by Ekman transport and can be expressed as

$$\frac{\partial z}{\partial t} = \frac{\tau_x}{\rho f R} \tag{2}$$

where τ_x is the alongshore component of the wind stress (i.e., projected on the mean southwestern barrier reef

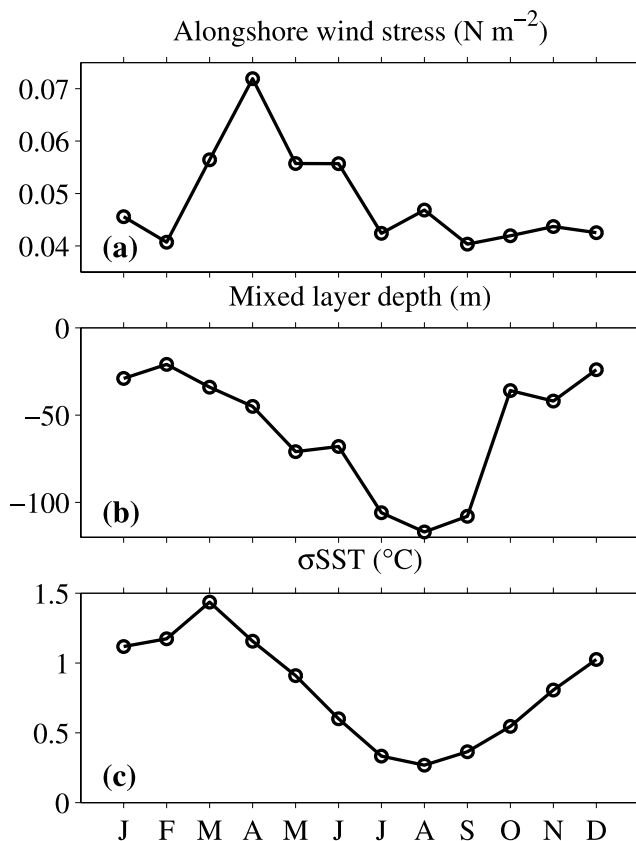


Figure 7. Monthly long-term means of (a) alongshore wind stress, (b) mixed layer depth, and (c) SST standard deviation.

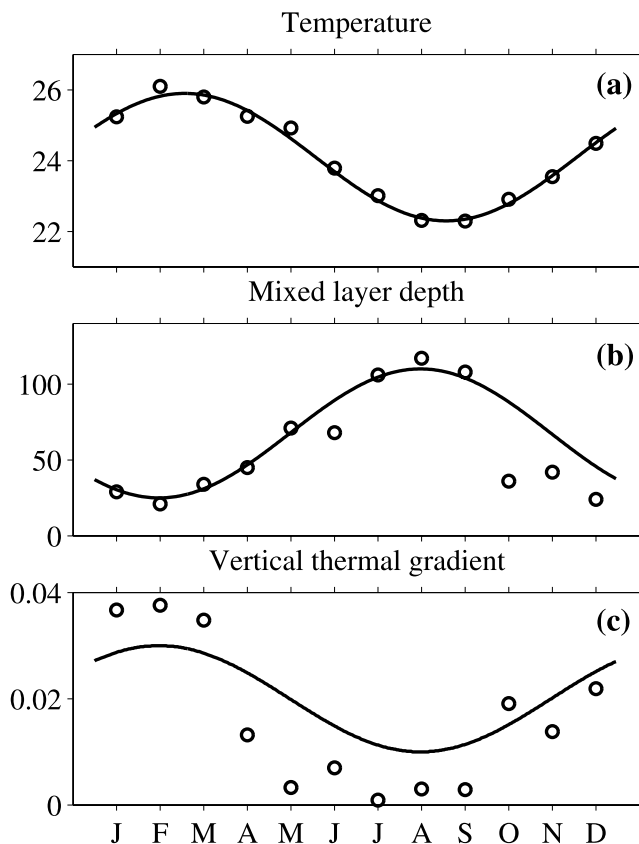


Figure 8. Seasonal harmonics used to build the upwelling index compared to long-term observed monthly means for (a) temperature at the coastal station, in degrees Celsius, (b) mixed layer depth, in meters, and (c) vertical thermal gradient, in °C m⁻¹.

direction, 45° as seen on Figure 1), f is the Coriolis parameter and R is the across-shore length scale of upwelling. Note that this term includes the widely used Bakun upwelling index ($\tau_x/\rho f$) [Bakun, 1973]. Assuming that $\partial T/\partial z$ and H do not vary at timescale smaller than a few days, integrating equation (1) over this period gives the temperature variation ΔT from day $d - n$ to day d which defines our simple physical model:

$$\Delta T_{d-n}^d = \frac{1}{R} \frac{\partial T}{\partial z} \int_{d-n+1}^d \frac{\tau_x}{\rho f} dt + \frac{1}{\rho C_p H} \int_{d-n+1}^d F dt \quad (3)$$

[20] The model was daily forced by atmospheric variables (τ_x , F defined as the sum of the latent heat flux and solar radiation flux), while oceanic variables (SST, H , $\partial T/\partial z$) only provided information about the background seasonal state. Annual harmonics of oceanic variables were estimated on the basis of the observed long-term monthly means (Figure 8), as in other simple upwelling models [Chiswell and Schiel, 2001].

[21] By construction, interannual variations of oceanic variables were thus neglected. However, ENSO-related anomalies in the water column have been observed around New Caledonia. They can reach -0.5°C ($+0.5^\circ\text{C}$) during an El Niño (La Niña) event at the surface, and decrease down to 100-m depth where they become insignificant [Delcroix

and Lenormand, 1997]. For $\partial T/\partial z$, this corresponds to interannual variations around $0.01^\circ\text{C m}^{-1}$ in amplitude, thus smaller than the observed seasonal variations by a factor of 4 (Figure 8c). The same ratio applies for SST variations (Figure 8a). H has no clear interannual signature around New Caledonia [Lin et al., 2004].

4.3. Calibration and Application of the Model

[22] The calibration of the model consisted of tuning parameters so that the modeled ΔT reproduced as best as possible the observed ΔT over the 1992–2004 period. We adjusted timescale n in equation (3) to maximize the correlation between the modeled and observed ΔT . We adjusted the value of R and the amplitude of the $\partial T/\partial z$ annual harmonic to fit the observed ΔT standard deviation, at annual and seasonal timescale, respectively. Sensitivity tests were also conducted with the simple ΔT model. They consisted of successively removing the heat flux term in equation (3) and forcing $\partial T/\partial z$ to a mean annual value, to check the sensitivity of ΔT to air-sea heat fluxes and seasonal changes in the temperature stratification.

[23] The calibration phase is summarized in Figure 9 for the three model configurations: one with a constant $\partial T/\partial z$ and no heat flux, a second with a seasonally varying $\partial T/\partial z$ and no heat flux, and a third which includes a seasonally varying $\partial T/\partial z$ as well as the air-sea heat fluxes. Modeled and observed ΔT time series are compared using two independent statistical parameters: correlation and standard deviation. Correlation is dependent on the number of days over which the model is applied (Figure 9a). For each

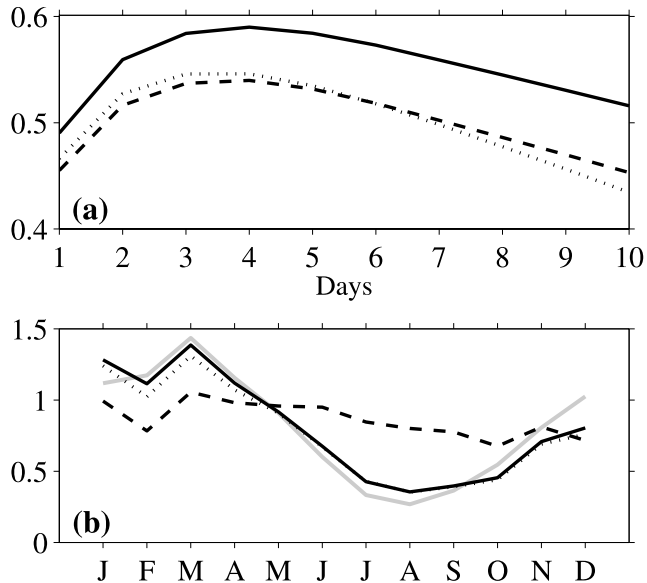


Figure 9. (a) Correlation between the modeled and observed ΔT , expressed as a function of the number of days over which the model is applied (n in equation (3)) and (b) standard deviation of the modeled ΔT , expressed as a function of the calendar month, for three model configurations: constant $\partial T/\partial z$ with no heat flux (dashed line), seasonally varying $\partial T/\partial z$ with no heat flux (dotted line), and seasonally varying $\partial T/\partial z$ with heat flux (solid line), compared with the observed ΔT standard deviation (grey line), in degrees Celsius. All correlations are significant at the 99% confidence level ($r_{99} = 0.08$).

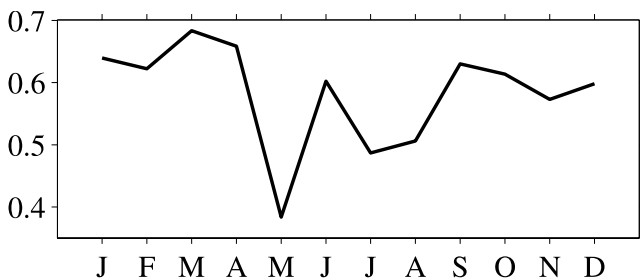


Figure 10. Correlation between the modeled and observed ΔT , expressed as a function of the calendar month where the correlation is done, for the complete model configuration. All correlations are significant at the 99% confidence level ($r_{99} = 0.23-0.25$).

configuration, the correlation is maximal where the model is set to reproduce ΔT over a 4-day period, which is consistent with the observed timescale of the upwelling process. A 4-day value for n in equation (3) is therefore chosen for all model configurations. The basic version of the model produces a reasonably good correlation given its simple physics. Introducing a seasonally varying $\partial T/\partial z$ only improves it very slightly. However, the heat flux term, whose contribution to ΔT is 5–10 times as small as the

strictly upwelling-related ΔT in the monthly standard deviation, increases the correlation by about 10% up to a 0.59 value. Figure 9b shows that using a seasonally varying $\partial T/\partial z$ in the model is crucial. With a constant $\partial T/\partial z$, the modeled ΔT has weak seasonal fluctuations; it is smaller than observed in summer but up to 3 times as large in winter. A seasonally varying $\partial T/\partial z$ corrects this problem as it modulates the amplitude of the SST response to wind-forced upwelling (see equation (3)). Introducing heat fluxes in the model formulation hardly affects the standard deviation.

[24] The seasonal modulations in the correlation skill (Figure 10) are not dependent on the model configuration. They are presented for the full version of the model, which will be used from now on. As expected, the best correlation is produced in March which is the peak of the upwelling season. Significant correlations are also found in June, September, and October, out of the upwelling season (Figure 7c), suggesting that while upwelling events have a weaker signature, the mechanism is still predominant for SST variations at a few days timescale. Although SST variability in May suggest an important upwelling activity, the model reaches its lowest correlation skill at that time of the year, which may be due to large-scale processes not accounted for in the model.

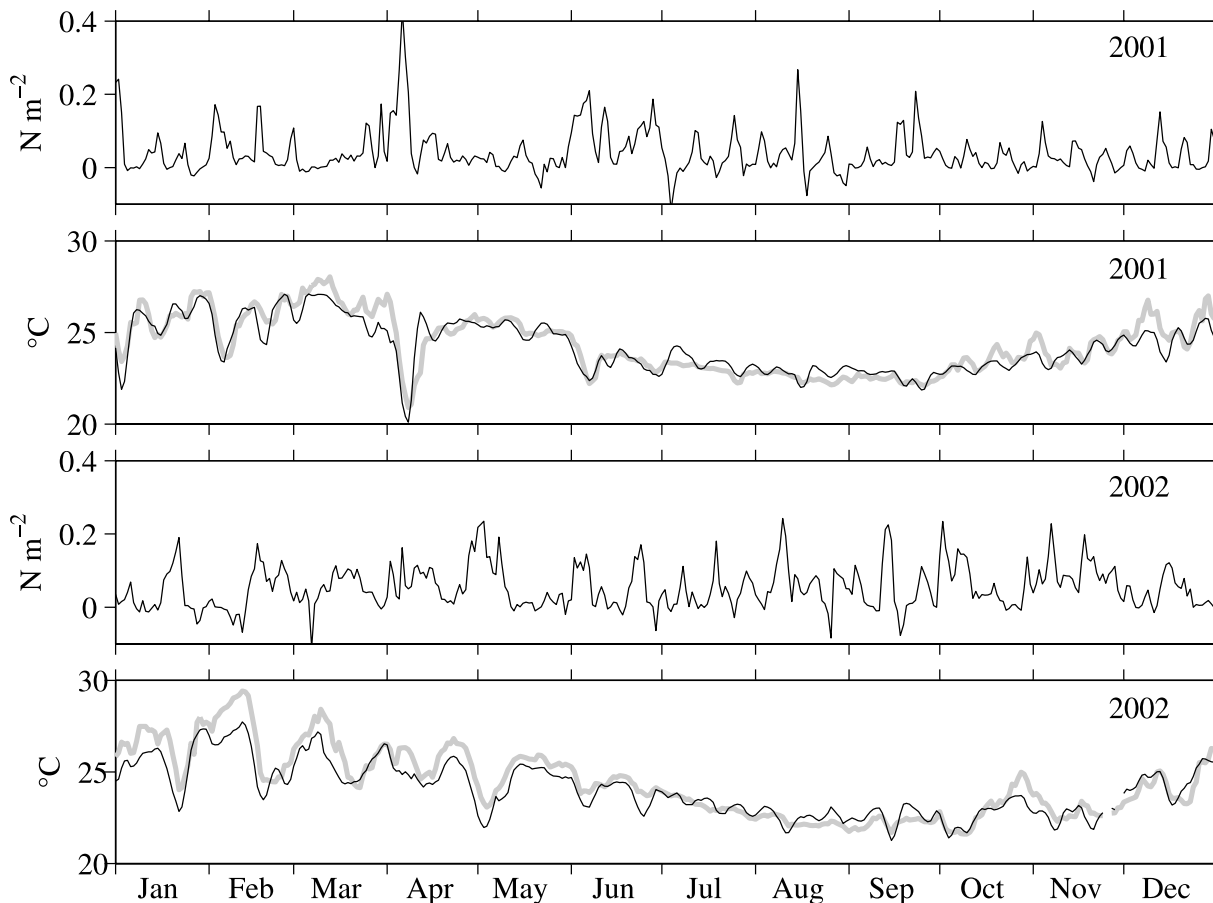


Figure 11. Time series of NCEP alongshore wind stress and SST (thick grey line: observed at the coastal station; black line: modeled) over the years 2001 and 2002.

[25] The calibration gives for R , the across-shore length scale of upwelling, a value close to 8.5 km. This is consistent with the observed extension of coastal coolings, in most cases around 10 km, although cold plumes extending 50 km off the barrier reef sometimes appear [Hénin and Cresswell, 2005] (Figure 3). The stratification-dependent Rossby radius of deformation, which is about 50 km around New Caledonia [Chelton *et al.*, 1998], was first proposed as a measure of R [Yoshida, 1955]. However, later theoretical studies suggested R is much smaller than the Rossby radius because of the local weakening of the stratification by upwelling [Pedlosky, 1978], and coastal friction [Mitchum and Clarke, 1986]. Dynamical studies also showed, in agreement with our finding, that upwelling is confined to a very narrow coastal band [Capet *et al.*, 2004].

[26] The daily vertical upwelling speed could be calculated from the observed alongshore wind stress (equation (2)), with R set to 8.5 km, as in previous studies [Bourque and Kelley, 1995]. The calculation suggests that a 0.11 N m^{-2} alongshore wind stress, a frequently reached value (Figure 5a), generates an upwelling speed of about 20 m d^{-1} . The strongest peaks in trade wind are likely to generate upwelling speeds in the $40\text{--}80 \text{ m d}^{-1}$ range. These large values would need to be confirmed by more direct measurements.

[27] While the model was calibrated to maximize its skill, its simplicity means the modeled and observed ΔT time series do not match perfectly. The two SST time series are compared for years 2001 and 2002 in Figure 11, to illustrate the model skill and help identify some recurrent biases. Years 2001 and 2002 show slightly different wind variability structures and are weakly affected by ENSO-related interannual variability which could induce shifts in the background seasonal harmonic. In 2001, a very strong trade wind burst occurred during the first April week, giving birth to the largest upwelling event in the year, which is well reproduced by the model. This is not the case for the following SST rise or the SST drop in mid-March, the latter because it is obviously not related to an upwelling process in this no-wind period. In mid-August, a secondary short-lived wind peak occurred, whose SST signature is damped in the model by the winter $\partial T/\partial z$ coefficient. In early July, the model overestimates the SST rise in response to a negative wind peak, as downwelling does not act in a symmetrical way on SST [De Szoeke and Richman, 1981]. Compared to year 2001, year 2002 had more regular wind variability with two distinct seasons: the first half of the year consisted of a succession of relatively strong trade wind episodes lasting one to several weeks while the second half had smaller mean trade winds with shorter strong events. The modeled summer upwelling events are generally in phase with the observed cooling events but their amplitude is often larger than observed. This may be due to a durable decrease of $\partial T/\partial z$ by the successive upwelling events, a feedback which is not included in the model as it is based on a $\partial T/\partial z$ climatology.

5. Discussion

[28] Although our simple model captures reasonably well the observed SST variations, it has important limitations. The vertical thermal gradient is a key factor in our model. It

is taken here as a coefficient constant with depth, which is obviously a rough approximation (Figure 2). However, its seasonal harmonic is only partly constrained by the available $\partial T/\partial z$ data (Figure 8c) and for another part by the seasonal calibration (Figure 9b), to compensate for the simplified physics of the model. Using a linear interpolation based on the observed long-term monthly means of $\partial T/\partial z$ instead of a seasonal harmonic in fact reduces the model skill. Considering variations in the vertical stratification at the seasonal timescale only is another limitation of our model. At daily timescale, H and $\partial T/\partial z$ are expected to highly interact with upwelling as upward velocity tends to shallow the mixed layer, strong wind tends to deepen it by mixing, and heat fluxes tends to stabilize the stratification [De Szoeke and Richman, 1981]. Also, while there are relatively small interannual variations in the subsurface stratification, interannual variability is included in the model through the wind term only.

[29] Despite these limitations, the model demonstrates that coastal upwelling can explain a large part of the daily SST variations off southwestern New Caledonia, and in particular the strong cooling events observed in summer. Heat fluxes contribute far less than upwelling to daily SST variations. The characteristic scales of upwelling, deduced from the model calibration, are around 10 km for the across-shore length and 4 days for the timescale. They are consistent with the values proposed by Hénin and Cresswell [2005]. The most interesting finding of this study is that, off New Caledonia, upwelling acts at daily timescale, while its SST signature is modulated at seasonal timescale by the subsurface stratification. This explains why, paradoxically, the strongest cooling events occur during the months with the warmest SST. In contrast with eastern boundary systems, the seasonal cycle of SST is not driven by upwelling [Nykjaer and Vancamp, 1994]. To investigate further into the dynamics of the upwelling system off New Caledonia, and in particular its interaction with large-scale processes, a regional ocean circulation model is now being adapted to the region.

[30] We only hinted at the implications of upwelling off New Caledonia. During summer cooling events, the biological response related to nutrients supply results in coastal chlorophyll concentrations enhanced by a factor of 10 compared to the offshore values. However, these concentrations remain 10 times smaller than those observed in eastern boundary upwelling centers [Rutllant *et al.*, 2004] because of the oligotrophic environment. The biological impact is probably modulated by the strong seasonality in subsurface nutrients availability observed in the region [Ridgway *et al.*, 2002]. Nutrient enrichments can also be a limiting factor for coral growth, which makes upwelling a strong candidate to explain the noted retardation in the settlement of the southwestern reef of New Caledonia, at geological timescales [Montaggioni *et al.*, 2006]. As global warming of SST, another important factor for coral growth, threatens the future of coral reefs [Hughes *et al.*, 2003], upwelling-related cooling may help the barrier reef of New Caledonia to adapt to global change.

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References

- Bakun, A. (1973), Coastal upwelling indices, west coast of North America, 1946–71, *NOAA Tech. Rep. NMFS SSRF-671*, U.S. Dep. of Comm., Washington, D. C.
- Bourque, M. C., and D. E. Kelley (1995), Evidence of wind-driven upwelling in Jacques-Cartier Strait, *Atmos. Ocean*, *33*, 621–637.
- Brink, K. H. (1983), The near-surface dynamics of coastal upwelling, *Prog. Oceanogr.*, *12*, 223–257.
- Capet, X. J., P. Marchesiello, and J. C. McWilliams (2004), Upwelling response to coastal wind profiles, *Geophys. Res. Lett.*, *31*, L13311, doi:10.1029/2004GL020123.
- Chelton, D. B., R. A. De Szoeke, M. G. Schlax, K. El Naggar, and N. Siwertz (1998), Geographical variability of the first baroclinic Rossby radius of deformation, *J. Phys. Oceanogr.*, *28*, 433–460.
- Chiswell, S. M., and D. R. Schiel (2001), Influence of along-shore advection and upwelling on coastal temperature at Kaikoura Peninsula, New Zealand, *N. Z. J. Mar. Freshwater Res.*, *35*, 307–317.
- Delcroix, T., and O. Lenormand (1997), ENSO signals in the vicinity of New Caledonia, south western Pacific, *Oceanol. Acta*, *20*, 481–491.
- De Szoeke, R. A., and J. G. Richman (1981), The role of wind-generated mixing in coastal upwelling, *J. Phys. Oceanogr.*, *11*, 1534–1547.
- Hénin, C., and G. R. Cresswell (2005), Upwelling along the western barrier reef of New Caledonia, *Mar. Freshwater Res.*, *56*, 1005–1010.
- Hughes, T. P., et al. (2003), Climate change, human impacts, and the resilience of coral reefs, *Science*, *301*, 929–933.
- Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.
- Lin, Y., X. You, and Y. Guan (2004), Interannual variability of mixed layer depth and heat storage of upper layer in the tropical Pacific Ocean, *Acta Oceanol. Sin.*, *23*, 31–40.
- Météo-France (1995), *Atlas Climatologique de la Nouvelle-Calédonie*, Nouméa, New Caledonia.
- Mitchum, G. T., and A. J. Clarke (1986), The frictional nearshore response to forcing by synoptic scale winds, *J. Phys. Oceanogr.*, *16*, 934–946.
- Montaggioni, L., F. Le Cornec, T. Corrège, and G. Cabioch (2006), Coral barium/calcium record of mid-Holocene upwelling activity in New-Caledonia, south-west Pacific, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, doi:10.1016/j.palaeo.2005.12.018, in press.
- Nykjaer, L., and L. Vancamp (1994), Seasonal and interannual variability of coastal upwelling along northwest Africa and Portugal from 1981 to 1991, *J. Geophys. Res.*, *99*, 14,197–14,207.
- Pedlosky, J. (1978), A nonlinear model of the onset of upwelling, *J. Phys. Oceanogr.*, *8*, 178–187.
- Petit, M., and A. Ramos (2002), From receiving stations to concept: Survey of the Environment Assisted by Satellite (SEASnet), a net for research and development, paper presented at ESA/ESRIN Workshop, Eur. Space Agency, Frascati, Italy.
- Ridgway, K. R., J. R. Dunn, and J. L. Wilkin (2002), Ocean interpolation by four-dimensional weighted least squares-Application to the waters around Australasia, *J. Atmos. Oceanic Technol.*, *19*, 1357–1375.
- Rutllant, J. A., I. Masotti, J. Calderon, and S. A. Vega (2004), A comparison of spring coastal upwelling off central Chile at the extremes of the 1996–1997 ENSO cycle, *Cont. Shelf Res.*, *24*, 773–787.
- Yoshida, K. (1955), Coastal upwelling off the California coast, *Rec. Oceanogr. Works Jpn.*, *2*, 8–20.

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